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REPORT OF CONFERENCE ON SOIL TRAFFICABILITY PREDICTION
HELD AT U. S. ARMY ENGINEER WATERWAYS EXPERIMENT
STATION ON 29-30 NOVEMBER 1966

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

April 1967

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SOIL TRAFFICABILITY PREDICTION

U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
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Foreword

A conference on Soil Trafficability Prediction was held at the
U. S. Army Engineer Waterways Experiment Station on 29-30 November 1966.
The conference and presentations were prepared under the general supervision of Mr. W. G. Shockley, Chief of the Mobility and Environmental Division; Mr. S. J. Knight, Assistant Chief, Mobility and Environmental Division; Mr. W. E. Grabau, Chief, Terrain Analysis Branch; and Mr. M. P. Meyer, Chief, Classification and Prediction Section. The technical papers (included in this volume as Appendixes A-H) were prepared by the following personnel of the division: Messrs. C. A. Carlson, A. R. McDaniel,
J. G. Collins, H. D. Molthan, M. P. Meyer, and Miss Margaret H. Smith.

Colonel John R. Oswalt, Jr., CE, was Director of the Waterways
Experiment Station. Mr. J. B. Tiffany was Technical Director.

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REPORT OF CONFERENCE ON SOIL TRAFFICABILITY PREDICTION

U. S. Army Engineer Waterways Experiment Station

29-30 November 1966

Background

1. A conference on soil trafficability prediction was held at the U. S. Army Engineer Waterways Experiment Station (WES) on 29-30 November 1966 to review the progress of studies related to soil trafficability prediction conducted since the last consultants' meeting in 1958 and to afford the consultants an opportunity to comment on problem areas and make recommendations for future research.

2. This paper summarizes the conference. Included herein are (a) résumés of the presentations and succeeding discussions (complete texts of the technical papers are included as appendixes to this miscellaneous paper); (b) exhibit 1, the conference agenda; (c) exhibit 2, the list of attendees; (d) exhibit 3, proposed future plans; and (e) exhibit 4, the report prepared by the Board of Consultants.

3. Colonel John R. Oswalt, Jr., Director, WES, opened the meeting with a welcoming statement to the consultants and visitors. Mr. W. G. Shockley, Chief of the Mobility and Environmental Division, WES, and chairman of the conference, outlined the procedures and agenda which were to be followed. He charged the consultants with the responsibility of compiling recommendations for presentation during the final session of the conference on the morning of the second day, pointing out that presentations and discussions of papers would require the entire first day.

4. Mr. S. J. Knight, Assistant Chief of the Mobility and Environmental Division, reviewed the division's research programs. He noted that all programs are under the cognizance of the U. S. Army Materiel Command (AMC). These include three continuing programs funded by AMC and four short-term programs funded by other agencies. A movie was presented which described the principal earth science research conducted by the WES for AMC. At the invitation of Mr. Shockley, Mr. P. F. Carlton, AMC,

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commented on the role of Army research and the need for results which can be of practical use to the Army.

5. Mr. R. F. Jackson of the Office, Chief of Engineers, and previously with AMC, presented the latest approach formulated by the AMC Earth Science Study Group for conducting Army research and development work in the earth science field. The approach requires a means for dealing with a problem under specific battlefield conditions or situations and a system for describing battlefield conditions in a manner which brings reality into the development process. Programs following this approach are characterized by environmental factors and materiel items that are quantitatively defined and by analytical or mathematical models that relate the environment to its effect on materiel. The program also must be based on a functional classification of Army activities and must be adequately supported by basic research. He presented the functional outline of such a program, termed the Battlefield Environment Research Program, and means for its implementation.

6. Mr. M. P. Meyer presented a general review of the WES trafficability studies. He discussed the general scope and accomplishments of three study phases, i.e., contact (field measurement by mechanical means), noncontact (remote measurement by electromagnetic wave sensing devices), and indirect (estimation based on information obtained from various data sources). He discussed in detail three different approaches for estimating trafficability by indirect means, i.e., by airphoto interpretation, by a trafficability classification system, and by prediction of the change in trafficability with time using soil and weather information. He traced the progression of trafficability studies from their inception in 1945 to the present.

Soil Moisture Prediction

"Methods of Soil Moisture
Prediction for Trafficability Pur-
poses" by C. A. Carlson (Appendix A)

7. The soil moisture prediction method was derived to predict, on a

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daily basis throughout a year, the net moisture contents of the 0- to 6-in. and 6- to 12-in. soil layers. The method was developed empirically from daily field measurements of soil moisture content and rainfall. For each test site, prediction relations were determined for accretion, depletion, and auxiliary values. Predicting was accomplished by a simple book-keeping procedure of adding or subtracting water by amounts determined from the prediction relations. For some sites the prediction was modified to account for influences such as persisting water tables or storms less than minimum. Predictions made during the year of record for 126 sites had an average deviation between predicted and measured moisture contents of ±1.5 percent by weight.

8. Each set of relations was applicable only to the specific site used for the derivation. To extend the application to areas without detailed records, a set of average relations was derived from data collected in the United States through 1954. The average deviation for 24 sites used in deriving the average relations was ±3 percent moisture content. In a test on 601 sites with rainfall gages located from 1 to 5 miles from the sites, the average deviation was ±4 percent moisture content. Large deviations for soils with high organic or high clay contents and soils influenced by water tables indicated a need for improving the average relations for these soils. Results of a study in Puerto Rico in 1956 confirmed this need. Efforts to improve the relations (using United States data collected in 1958) were not fruitful. The average relations were useful in some U. S. Forest Service and U. S. Naval Radiological Defense Laboratory applications.

"Effects and Deficiencies
of Factors Used in WES Soil
Moisture Prediction System"
by A. R. McDaniel (Appendix B)

9. The factors used in the soil moisture prediction system were examined to determine the effect of each on prediction accuracy and to reveal deficiencies of the system which might be corrected. Errors resulting from use of an incorrect initial moisture content decrease with the passage of time and generally with the occurrence of rainfall, until the error no longer exists. An error in field maximum and minimum moisture

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contents leads to a continuous error in predicted moisture content; improvements are needed in the equations for estimating these values. Frequent storms near an estimated minimum size and errors in estimating rainfall amounts generally introduce errors in prediction. The use of linear and separate accretion relations for rainfall and available storage was questioned; an exponential relation that includes both rainfall and available storage was suggested as a substitute. A means for accurately estimating transition dates is needed to eliminate errors in predicted depletions. It was suggested that additional factors be used in the estimation of depletion rates and that an exponential expression of moisture loss with time be adopted for use. Other means of improving the accuracy of prediction include the consideration of such factors as surface air flow and heat flux, time periods shorter than daily, and an increase in measurement accuracy. It was noted, however, that improvement in accuracy may be limited because of the inherent natural variation of the soil. Because of the deficiencies of the factors in the present scheme, it was suggested that a new soil moisture prediction system be developed employing new data-collection techniques.

Discussion

10. Dr. W. A. Raney asked if predictions had been correlated with rainfall distribution within geographical regions of the United States. He stated that in some areas rainfall can vary greatly over a short distance. Mr. Carlson replied that no general rainfall distribution studies had been made by the WES, but that the variability was recognized. He cited the Hawaiian study which showed average annual rainfalls ranging from 10 to 200 in. within a few miles across a mountain pass, and the Mississippi alluvial soil study which showed that the accuracy of prediction based on records from site rain gages was practically the same as that based on records from surrounding official weather stations 30 miles apart. He also cited the Warren County variation study which showed relatively large differences in average soil moisture content between adjacent sampling areas despite relatively uniform rainfall over the testing area.

11. In response to questions by Dr. Raney and Dr. D. McClurkin regarding the size of the area of concern to trafficability, Mr. Shockley

replied that the area would depend on the military engagement; it can be the size of a mudhole, or an area of many square miles.

12. Dr. Raney said that water sources other than rainfall may influence soil moisture conditions, and that topography needs to be considered because of its effect on the surface and subsurface flow of water. Mr. W. J. Turnbull said that the number of possible variables influencing soil moisture is so great that consideration of all may not be justified. From a practical viewpoint one should be satisfied with a certain amount of error; however, the amount that can be tolerated would depend upon the size of the area for which the prediction is being made. Dr. Raney asked how much error can be tolerated, and Mr. Knight replied that in some soils a change of 0.1 of 1 percent moisture content can change a "go" condition to one of "no go." Mr. A. C. Orvedal concurred with Mr. Turnbull's appeal for a practical approach and commented that it was remarkable that any prediction method had been developed in view of the problems involved. He said the main interest for prediction is in wet soils, and that the effects of minimum storm size under dry conditions are of little concern.

13. Dr. Raney asked if the thickness of the wetting zone above the water table was measured and considered in terms of its effect on soil moisture. Mr. Carlson answered that a water table is usually measured to a depth of 4 ft and moisture content to a depth of 12- or 18-in., and that the water table effect, in general, is believed to be significant only when the surface of a water table lies within 2 ft below the layer in question.

Soil Strength Prediction

"A Tentative Soil Strength Prediction
System" by J. G. Collins (Appendix C)

14. This paper presented relations between rating cone index (RCI) and soil moisture content (MC), and between MC (at a given RCI level) and other pertinent soil and site factors. Data from the 6- to 12-in. soil layer from 38 sites were used in the analysis. Results confirmed that RCI decreases with increases in MC. Two RCI-MC equation constants, i.e. MC at 100 RCI and MC at 200 RCI, were computed. Three ways of relating these equation constants to soil and site differences were explored: (a) by

soil classes of the Unified Soil Classification System (USCS) and the
U. S. Department of Agriculture (USDA) textural classification system,
(b) by individual soil and site factors, and (c) by multiple soil and site
factors. Results indicated that RCI at a given MC increases and that
RCI-MC slopes become flatter with increase in plasticity or decrease in
grain size of the soil. Multiple factor relations were used to predict
RCI; the average prediction accuracy was +30 RCI units. The study indi-
cates that RCI is sensitive to very small changes in soil properties.

Discussion

15. Dr. McClurkin questioned the use of nonquantitative indexes
in the factor analyses. Mr. Shockley explained that plasticity index is
calculated from plasticity limits measured quantitatively in terms of per-
cent moisture content. Mr. Carlson explained that wetness index is based
on depth of wetting and depth to a water table, and that the category
numbers are assigned considering the depths.

16. Mr. J. P. Sale discussed the desirability of combining the soil
moisture and soil strength prediction systems, field testing the combined
system, and if acceptable, putting it in a probabilistic form that would be
useful to the Army. Mr. Shockley replied that this suggestion was in the
plans for the future and it would be discussed later in the day.

17. Mr. R. A. Liston questioned the use of linear relations based
on logarithmic values to estimate arithmetic quantities because error is
introduced. Dr. H. J. Nikodem said that the procedure does not result in
an exact expression but that it is generally acceptable.

18. Dr. Nikodem suggested that moisture be measured in 1-in. layers
and that a diffusion equation be used for integrating the several layers.
Mr. McDaniel stated that his system for predicting soil moisture, to be dis-
cussed later in the day, permitted prediction for a layer of any thickness.

Factors Influencing Soil Moisture and Soil Strength

"Influence of Water Tables on
Soil Moisture and Soil Strength"
by J. G. Collins (Appendix D)

19. This paper presented some of the findings of three water table

studies made in Mississippi-Alabama, Arkansas, and Oregon. The data indicate differences in the moisture regimes of the 6- to 12-in. soil layer between high and low water table sites. In general, field maximum soil moisture contents were higher at high water table sites, and longer periods of time were required for the moisture to deplete from field maximum to a level common to both types of sites. Data from many sites indicate that the rating cone index decreases with a rise in water table; after the soil has reached the field maximum moisture content, the rating cone index remains relatively constant with a further rise in the water table. An inception date, accretion-rainfall relation, and recession rate can be used to characterize a water table. The data indicate that the time of water table inception is related to cumulative rainfall, local topography of the area, and stratification of the soil; the accretion-rainfall relation is related to soil pore-size distribution; and the recession is related to soil permeability, local topography of the area, soil pore-size distribution, and rate of evapotranspiration.

"Influence of Soil Variability on
Soil Moisture and Soil Strength Predictions" by H. D. Molthan (Appendix E)

20. Four studies of soil variability were reviewed and pertinent data from each were presented. The significance of these data as they relate to soil moisture and soil strength predictions was discussed, and the number of samples necessary for a statistically significant estimate of the various soil properties pertinent to trafficability was calculated. The variability expressed in the data was found to be derived from two sources: (a) point to point horizontal variation, and (b) variation due to inclusion of anomalous soil areas. The source of variation was found to affect not only the statistical handling of the data, but also the usefulness of any prediction made from the data. A greater knowledge of the sources and magnitudes of variations within the soil is necessary before satisfactory predictions of soil trafficability can be made.

Discussion

21. With reference to the discussion on water tables and the figure

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showing water table recession rates in Oregon, Mr. Orvedal asked whether
the increase in recession rate at lower depths was due to seepage or river
influence. Mr. Collins said that in this instance seepage was the factor;
however, at one site in Arkansas the water table was influenced by a river
1/2 mile away.

22. Mr. Orvedal said that military trafficability problems generally
occur in soils with moisture contents greater than field capacity (or 0.06-
atm tension), and suggested that efforts be concentrated in studies at this
moisture condition. Dr. D. R. Freitag stated that the moisture range
should not be limited because new types of heavy vehicles have higher soil
strength requirements. Mr. Collins said the moisture limits would depend
on soil type. Mr. Carlson referred to certain critically soft soils in
Thailand having no water table.

23. Mr. Shockley asked if soil morphological features, agricultural
practices, or natural vegetation could be used as indicators of soil wet-
ness. Dr. J. C. Goodlett stated that canopy height does not follow the
ground contour; bottomland trees grow taller reflecting a higher moisture
condition. He found that shapes of the slope show a greater relation to
soil wetness than does the slope itself. Mr. Carlson said that results
of the Warren County variation study indicated the need for considering
the influence of the concavity of the ground surface on its moisture-
strength condition. He questioned the means for expressing concavity
without using an index system. Dr. Goodlett said radius of curvature can
be used. Dr. Raney suggested using airphotos or satellite systems to
provide information on terrain conditions.

Comparison of Factors for Temperate and Tropical Climates

"Comparison of Soil Moisture
Prediction Factors for Tem-
perate and Tropical Climates"
by Miss M. H. Smith (Appendix F)

24. This study was made to compare the soil moisture prediction
factors for temperate climates (continental United States and Alaska) and

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tropical climates (Caribbean area, Hawaii, and Thailand). The information from the soils studied in the tropics was biased in that the sites were selected primarily in wet, low-lying areas. The results of the study in Thailand differed from those of the other tropical studies with respect to prediction factors; Thailand, therefore, was not included in the statements about season and field maximum and field minimum moisture contents.

25. The tropical soils studied had only one season with reference to depletion relations; the temperate soils had more than one. Tropical soils had higher minimum size storms than those of temperate soils. The average field maximum and field minimum moisture contents for all sites were much higher for tropical soils than for temperate soils. Average annual rainfall was greater in tropical areas than in temperate areas. Accretion relations for soils of both climates were similar, although the tropical soils had slightly higher soil moisture accretions for the same amount of rainfall. The depletion relations for the tropical soils varied greatly. Predictions of soil moisture based on specific relations were adequate for both temperate and tropical climates. Tentative average prediction relations derived from data of studies in temperate areas were not applicable to soils of the Caribbean area and Hawaii; the prediction relations were not tested for soils in Thailand.

Discussion

26. Dr. Rancy commented that the prediction method was not correct because predictions could not be made with equal accuracy for soils in temperate and tropical climates. He suggested that a method based on energy balance would be universally applicable. Mr. Orvedal replied that the disparity in predictions between temperate and tropical soils may have been due to the fact that testing in the tropics was biased toward wet soil conditions. He concluded that if tests had been conducted on soils of all regions of the tropics, including deserts as well as wet regions, the results would have been different. Mr. Knight asked why the depletion rates varied more in the tropics than in the temperate areas. Mr. Orvedal replied that this could be attributed to greater differences in transpiration rates of the vegetation in the tropics.

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27. Mr. M. Soriano-Ressy asked if differences in the age of rock would result in differences in characteristics of temperate and tropical soils. Mr. Orvedal replied that the age of soil, not rock, is important. He commented on the unusual nature of some tropical soils that appear to change from coarse to fine texture with manipulation and other tropical soils that must be used in a wet condition for road construction.

Portrayal of Trafficability Conditions

"Predicting and Portraying Soil
Moisture on an Areal Basis in Costa
Rica" by A. R. McDaniel (Appendix G)

28. A system for predicting and portraying soil moisture on an areal basis was developed from data collected at 170 test sites in Costa Rica. Relations were derived for the 0- to 6-in. and 6- to 12-in. layers. Moisture contents above field minimum were predicted on the basis of exponential accretion and depletion relations. Factors included in the accretion relations were: last previous predicted moisture content, rainfall (if greater than 0.10 in.), moisture range (field maximum minus field minimum moisture content), predicted available storage, and an equation constant for all soils. Factors included in the depletion relations were: last previous predicted moisture content, number of elapsed days between significant rainfalls, and an equation constant for all soils. Five classes of soils were established, based on differences in moisture range between field maximum and field minimum moisture contents. Starting at moisture contents estimated from the antecedent month's rainfall, one-year predictions were made for each of the five soil classes using rainfall records from 83 stations in Costa Rica. A map for each of the soil classes was used to portray the predicted results on a given day. To make a map, predicted moisture contents above field minimum were plotted at points of each weather station, and isopleths were drawn to delineate areas of similar moisture content. Maps for three soil classes were drawn for five different days of the year to show the areal change in moisture content with season.

29. A statistical analysis was made of strength in terms of rating
cone index for soils of the 6- to 12-in. layer, which is the critical
layer for most U. S. Army vehicles. Data were obtained during wet-season
periods from more than 1300 sites, most of which were located in humid,
temperate regions of the United States. The information was used to de-
velop a scheme for classifying soils according to their trafficability.
The scheme considers soils classified in terms of both the USCS and the
USDA textural classification system, topography in terms of relative
position and water table, and two general levels of wetness. The clas-
sification scheme lists the soil types under each of four topography-
general wetness level conditions in order of decreasing median rating cone
index. Adjoining each soil type is a graph showing the probability of
"go" for a vehicle with known minimum soil strength requirements, i.e.
vehicle cone index. From these graphs, the analyst can estimate the
probability of a successful operation under given soil type, topography,
and general wetness level conditions. Given the choice of several routes
and vehicles, the analyst can determine which vehicles have the highest
probability of traversing a given route or which routes, on the basis
of probabilities, are best suited for given vehicles.

Discussion

30. Dr. Raney asked if moisture content entered into the clas-
sification scheme. Mr. Meyer replied that it is used indirectly in
determining the duration of the wet season; the classification is based
on strength at the average and highest moisture conditions of the soil
in the wet season. Mr. M. V. Kreipke asked if the scheme could be applied
throughout the world. Mr. Meyer replied that the scheme was developed
from data collected in humid, temperate areas of the United States but
that a similar scheme developed for Thailand had similar soil strength
relations, thus suggesting that the scheme would be applicable to other
tropical areas. A question by Mr. Kreipke asking if minimum soil strength
could be used as a guide for vehicle design precipitated a lengthy dis-
cussion on requirements for vehicle design. Mr. Sale said that the

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design of a vehicle required consideration not only of soft soil, but also of other military requirements, and that one requirement had to be balanced against another to provide an optimum design; there is no such thing as an all-purpose vehicle.

Plans for the Future

31. Exhibit 3 is a general plan for the future; it includes five programs designed to satisfy needs in battlefield environments for soil information relating to vehicle mobility, military construction support, and weapons. Specific plans are also presented for the immediate future.

32. Mr. Orvedal said it was difficult to divorce trafficability from mobility problems and asked if the proposed plans were part of a larger plan. Mr. Shockley replied that many other facets would be considered in the environmental studies. Mr. Jackson asked how the plan differed from current work. Mr. Shockley reviewed the four immediate tasks, pointing out the proposed direction of new efforts. Dr. A. A. Warlam asked if the program included single-pass considerations. Mr. Shockley said it would insofar as information could be gleaned from current data; however, the prediction manual would be based largely on 50-pass considerations. Mr. Sale asked if useful information could be obtained through the interpretation of airphotos of totally inaccessible areas. Mr. A. A. Rula said the real test is to write up the procedure and test it. Dr. Goodlett asked if battlefield information had been used for reference. Mr. Shockley replied that battlefield reports had been examined in a contract study by George Washington University; however, the data obtainable were too general and qualitative to satisfy the needs of WES.

Consultants' Recommendations

33. The Board of Consultants met during the morning of 30 November to formulate a report of recommendations. The report (exhibit 4) was presented by Dr. Raney to all conference participants.

34. Dr. Warlam suggested that moisture error be expressed on a relative basis, that future work be concentrated on low-strength soil conditions, and that consideration be given to using the tapered penetrometer to measure soil strength. Mr. Carlton expressed concern regarding the time which would be required to arrive at solutions if research is to be carried out on a theoretical basis. Dr. Raney remarked that a time limit cannot be placed on this research. Mr. Orvedal remarked that the program has been characterized by a series of short-run studies, and that the work should be viewed now as a long-range program and planned accordingly. Mr. Turnbull added that if such an approach is followed, the program should be funded accordingly. Mr. Shockley adjourned the meeting.

AGENDA

for

CONFERENCE ON SOIL TRAFFICABILITY PREDICTION

U. S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi
29-30 November 1966

Mr. W. G. Shockley, Chairman

First Day

Main Conference Room - Headquarters Building

0830	Welcome	Col. John R. Oswalt, Jr.
0835	Introduction	Mr. W. G. Shockley
0840	Mobility and Environmental Division Research Programs	Mr. S. J. Knight
0855	Movie - AMC-Sponsored Research at WES	
0910	Battlefield Environment Research Program	Mr. R. F. Jackson
0930	Coffee Break	
0950	Review of Trafficability Prediction Studies	Mr. M. P. Meyer
1010	Soil Moisture Prediction for Trafficability Purposes	Mr. C. A. Carlson
1040	Effects and Deficiencies of Soil Moisture Prediction System	Mr. A. R. McDaniel
1100	Discussion	Group Participation
1115	A Tentative Soil Strength Prediction System	Mr. J. G. Collins
1135	Discussion	Group Participation
1150	The Influence of Water Tables on Soil Moisture and Soil Strength	Mr. J. G. Collins
1210	Influence of Soil Variability on Soil Moisture and Strength Predictions	Mr. H. D. Molthan

(1 of 2 sheets) EXHIBIT 1

1230	Discussion	Group Participation
1245	Lunch	
1345	Comparison of Prediction Factors for Temperate and Tropical Climates	Miss M. H. Smith
1405	Discussion	Group Participation
1420	Coffee Break	
1440	Predicting and Portraying Soil Moisture on an Areal Basis in Costa Rica	Mr. A. R. McDaniel
1500	Soil Trafficability Classification Scheme	Mr. M. P. Meyer
1520	Discussion	Group Participation
1540	Plans for Future	Mr. M. P. Meyer
1600	Discussion of Future Plans	Group Participation
1630	Adjourn	

Second Day

0830	Consultants' Time (M&E Conference Room)
1030	Consultants' Report (Main Conference Room)
1200	Adjourn

EXHIBIT 1 (2 of 2 sheets)

CONFERENCE ON SOIL TRAFFICABILITY PREDICTION

U. S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi
29-30 November 1966

U. S. Army Materiel Command

Mr. P. F. Carlton

Office, Chief of Engineers

Mr. R. F. Jackson

Mr. J. P. Sale

Office of Chief of Research and Development

Mr. M. V. Kreipke

U. S. Army Tank Automotive Center

Mr. R. A. Lister

U. S. Army Natick Laboratories

Dr. L. W. Trueblood

Consultants

Dr. H. W. Lull, U.S.D.A. Forest Service
Mr. C. E. Molineux, U.S. Air Force Cambridge Research Laboratories
Mr. A. C. Orvedal, U.S.D.A. Soil Conservation Service
Dr. W. A. Raney, U.S.D.A. Agricultural Research Service
Dr. D. McClurkin, U.S.D.A. Forest Service
Dr. A. A. Warlam, Consulting Engineer

Observers

Dr. J. C. Goodlett, Department of Geography, Johns Hopkins University
Dr. H. L. Mills, Department of Biological Sciences, Marshall University

U. S. Army Engineer Waterways Experiment Station

Participants

Col. John R. Oswalt, Jr., Director
Lt. Col. G. E. Jester, Deputy Director
Mr. J. B. Tiffany, Technical Director
Mr. W. J. Turnbull, Chief, Soils Division
Mr. W. G. Shockley, Chief, Mobility and Environmental Division

Participants (Continued)

Mr. S. J. Knight, Asst Chief, Mobility and Environmental Division
Mr. M. P. Meyer, Chief, Classification and Prediction Section
Mr. C. A. Carlson, Classification and Prediction Section
Mr. J. G. Collins, Classification and Prediction Section
Mr. A. R. McDaniel, Classification and Prediction Section
Mr. H. D. Molthan, Classification and Prediction Section
Miss M. H. Smith, Classification and Prediction Section

Observers

Mr. Fred R. Brown, Chief, Technical Programs and Plans
Dr. D. R. Freitag, Chief, Mobility Research Branch
Mr. A. A. Rula, Chief, Vehicle Studies Branch
Mr. E. S. Rush, Chief, Soil-Vehicle Studies Section
Mr. B. R. Davis, Chief, Remote Sensing Section
Mr. J. K. Stoll, Chief, Obstacle-Vehicle Studies Section
Mr. R. R. Friesz, Chief, Military Activities Section
Mr. B. O. Benn, Chief, Data Development Section
Mr. J. G. Kennedy, Soil-Vehicle Studies Section
Mr. G. T. Ellis, Classification and Prediction Section
Mr. M. Soriano-Ressy, Data Development Section
Dr. H. J. Nikodem, Remote Sensing Section
Mr. G. E. Schabilion, Military Activities Section
Mr. William N. Rushing, Data Development Section

EXHIBIT 2 (2 of 2 sheets)

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Introduction

The research performed to date in soil moisture and strength prediction--including the specific studies discussed today--has been responsive to the Army's needs in only one area; namely, vehicle mobility. Because emphasis was originally on quick answers, the studies have been almost completely empirical and statistical. It is now deemed appropriate to view these particular studies in the light of all the Army's needs and from a more basic or fundamental standpoint. In other words, it is proposed that the research program be reexamined and a more fundamental plan of research be initiated based on the most realistic assessment of battlefield environments possible to make at this time.

The military uses for soil information are many and varied. Indeed, they are so many that WES intends to restrict itself to study of those in which the immediate needs appear to be greatest. In the terms of the Battlefield Environment Research Program, these are vehicle mobility, mobility construction support, and weapons. It is therefore proposed that a research program be developed around the requirements of these three functions.

The final products of the Battlefield Environment Research Program will be analytical or mathematical models relating terrain to military activities in such a way that performance can be predicted in any situation in which the terrain details are known with sufficient accuracy. These models undoubtedly will progress slowly, growing more and more accurate and sophisticated as more is learned about the detailed relations of terrain to military activities. At any one point in time, however, the model will hopefully represent the state-of-the-art at that time. One important concomitant of successful research and improved analytical models is more accurate data on terrain factors. Another is assurance that no pertinent factors in terrain-activities relations are left unconsidered or unstudied. Still another point is to establish, insofar as feasible, the detail and accuracy with which these factors must be measured.

(1 of 7 sheets) EXHIBIT 3

The subject of vehicle mobility is well known at WES but is by no means completely understood. There appear to be at least four major soil factors that affect vehicle mobility: (a) the strength or condition of the soil at the surface, (b) the strength or condition of the soil below the surface, (c) the change in strength of soil that occurs with disturbance (i.e., its sensitivity, or remoldability as we usually refer to it), and (d) the stickiness. Despite the fact that WES has studied this problem for many years and has obtained highly useful data for military purposes, WES personnel do not completely understand the phenomena involved.

The factors required for a mathematical model that will relate soil to mobility construction support are much less well understood. It is believed that they include the four factors already described (surface strength, mass strength, sensitivity, and stickiness), plus perhaps several more. Some of the additional factors undoubtedly are related to compactibility and compressibility; that is, they are those factors that control the possible packing arrangements of the soil particles, the ease with which such arrangements can be achieved, and the resulting soil response to external forces.

The factors that affect weapons are largely unexplored. There appear to be two major areas where research is needed: (a) the interactions between projectile and soil, and (b) the interactions between weapon supporting and stabilizing elements and the soil. It is hypothesized that the significant factors include all of those that are significant for vehicle mobility and mobility construction support, plus an indeterminate number of additional ones. One of these may be viscosity, or whatever property (or properties) controls the rate of propagation of shock waves through the soil.

General Plan for the Future

With the above background, a new general plan for a research program can be formulated. It will be comprised of five fundamental programs,

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each of which will consist of a number of relatively clearly definable
tasks and subtasks.

Program I: Development of
Improved Field Instruments

It is considered that research in the past has suffered significantly
because of inadequate data--both quantitatively and qualitatively. It is
deemed highly necessary that significant time and effort be devoted to
the development of improved instrumentation which will hopefully relieve
this "suffering." Three devices are presently required: (a) a reliable
soil moisture sensing device to permit economical measurements at intervals
as close as 15 minutes, if needed; (b) a recording cone penetrometer es-
pecially sensitive to surface conditions and amenable to consistent rates
of penetration in all soil conditions; and (c) a device, possibly a more
sophisticated version of the Cohron sheargraph, to measure surface prop-
erties of soil. For maximum utility, all of these instruments should be
easily portable, durable, reliable, etc.

Program II: Identification
of Significant Soil Factors

A list of significant soil factors will be compiled for each of the
military functions under consideration (vehicle mobility, mobility con-
struction support, and weapons). This program will consist of a survey
of the technical literature on the three military functions and related
topics. Laboratories involved in research in these and related topics
also will be contacted. The objective will be to compile a preliminary
list of significant factors, a summary of the resolution of measurement
required for each, any analytical or mathematical models related to the
specified military functions, and all devices, instruments, and techniques
currently used to measure the factors.

Program III: Development of Im-
proved Soil Measurement Procedures

Based on an analysis of the data obtained in the literature search,
an effort will be made to develop updated procedures for obtaining measure-
ments of the required factors in the field. Two fundamental tasks will
be involved.

Task 1. The new instruments developed in Program I will be field tested to ensure reliability.

Task 2. More rigorous methods of establishing valid sample sizes for soils of all types and under all conditions will be developed. The general outline of this task will involve consideration of each significant factor as identified by Program II, the development of a hypothesis to explain the causes of areal or depth variation of each factor, and an experiment for each factor designed to verify or disprove the hypothesis. This cycle will be repeated as many times as necessary.

Program IV: Development of Con-
current Research in Remote Sensing
Through Electronic Means and
Aerial Photographs and Indirect
Methods for Acquiring Terrain Data

If knowledge of soil properties is to be used in the terrain intelligence and materiel design cycles, a method (or methods) must be found for rapidly assessing the soil properties of large areas. In general, this implies the development of a capability for deducing or inferring those properties from noncontact sensing system data or images, or from indirect sources. For example, if a sufficiently good correlation between surface geometry, vegetation physiognomy, climate, and soil factor values could be found, then it would be "practical" to "predict" the soil factor value on the basis of the presence of a specific array of site characteristics which could be recognized on airphotos.

Task 1. Prediction of soil mass and soil surface strength from climatic and site information will be undertaken. It will be the aim of this task to move toward a more basic understanding of relations between soil strength and environmental factors.

> **Subtask 1.** An analytical or mathematical model will be developed that will describe in deterministic terms the reaction of soils to the applied stresses of the three military activities mentioned.

> **Subtask 2.** The movement and flow of water through soils will be studied more intensively. This subtask will be facilitated by the successful development of the instrumentation already referred to.

> **Subtask 3.** A method of describing significant site factors in

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quantitative terms will be developed so that such data can be used in valid analytical models for predicting the performance of soils. It is anticipated that descriptions will have to be developed for factors affecting evaporation losses, transpiration losses, hydraulic gradient, water accretion sources, and perhaps several others.

Task 2. Photo-interpretation keys will be developed for identifying soil factor values, specifically those related to the array developed as a product of Program II. This task is envisioned as an exploitation of information developed in Programs II and III, and in Task 1, Program IV. In general terms, the subtask structure is envisioned as follows.

Subtask 1. Study sites will be selected. Tentatively, study areas will be established in the following places: near Vicksburg, Miss. (floodplain and bluff complex); near Guanica, Puerto Rico (tropical thorn forest and savanna complex); near Manati, Puerto Rico (tropical cultivated floodplain and beach ridge complex); near Huntington, W. Va. (midlatitude complex of forest, cultivation, floodplains, and mountains); and near Tempe, Ariz. (Sonoran desert to mountain evergreen forests at high altitudes). Appropriate data will be measured.

Subtask 2. Up-to-date air photography will be obtained, and all possible soil conditions will be predicted through a yearly cycle, in as much detail as possible. The weather variations characterizing each site will be studied, and predictions will be made through each characteristic weather cycle.

Subtask 3. After the predictions have been made, the sites will be studied on the ground, and actual and predicted moisture contents will be compared. Conditions will be monitored through each characteristic cycle.

Subtask 4. Photo-interpretation systems and procedures will be updated as a result of the findings in subtask 3.

The tasks under Program IV will be conducted in cooperation with the Department of Botany, Marshall University, and the Department of Agriculture research establishment at Tempe, Ariz.

Program V: Development of
Improved Data Display Systems

If interpretation and prediction systems are to be used successfully for military purposes, the output must be in a form that can be readily employed. Furthermore, the flow of information, from data acquisition to storage to manipulation (or interpretation or analysis) to display, should be as rapid as possible. It is our conviction that this can be achieved

only by exploiting machine-processing to the fullest extent. In view of this, efforts will be made to automate every step in the information flow process.

Specific Plans for the Future

The foregoing presentation has referred to the general need for reorientation of the research program along the lines of the Battlefield Environment Research Program and has described a general plan of research. For the immediate future it is proposed to undertake specific items of research as described below.

Item 1

The present soil moisture-strength prediction system for small sites will be tested for accuracy. Although there exists a reasonably clear estimate of the accuracy with which the present system is able to predict soil moisture content and strength, a specific test, under simulated battlefield conditions, has never been made. Accordingly, it is proposed that such a test be made as soon as feasible. Results of the test are not expected to provide a final or ultimate answer to the question of how accurate the system is, but they should provide useful data in this direction and be useful as an inclusion in item 2.

The test will consist of several levels of prediction, beginning with only knowledge of soil type, topographic position, and published climatological data (minimum information assumed to be available to commanders in the field), predicting soil moisture content and strength on a seasonal basis, and progressing to a final level of prediction in which all the factors are known (because they have been measured) and "prediction" is made daily on the basis of actual measured samples.

Item 2

A technical bulletin for use by the Army in the field will be written, and if approved by the Army, it will be published. The bulletin will describe, in cookbook fashion, the various steps to be made in predicting soil moisture content and strength according to the present state-of-the-art. There is no doubt that the state-of-the-art will improve and demand

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a revision of the bulletin. The bulletin will be similar to the familiar TB ENG 37 in purpose and format.

Item 3

As a result of more fundamental moisture-strength studies, it is proposed that data previously collected for trafficability prediction purposes be reevaluated to determine what data can be profitably used in the development of a more accurate system of trafficability prediction. Additional data will be collected only when necessary to fill gaps in the prediction system.

Item 4

It is proposed to continue the water table studies with the specific objective of being able to determine where, when, and for how long water table conditions will exist. To achieve this objective, studies of a more fundamental nature will be undertaken to provide a better understanding of water table environmental factor relations.

REPORT OF CONSULTANTS

Introduction

1. The presentation of papers by personnel of the Mobility and Environmental Division was well organized and thorough; it reflected careful preparation by a diligent and competent staff. We, the members of the Board of Consultants, extend our compliments to Mr. Shockley and all others concerned for a job well done.

2. The Board of Consultants recognizes that a research program, in the final analysis, is the responsibility of those to whom it has been charged. In light of our experience in different but related fields of interest, we can do little more than recommend courses of action which may hasten the fulfillment of the research program objectives. The decision as to whether a recommendation is implemented must be made by those having full knowledge of other existing and proposed research programs, current emphasis in requirements by the sponsor, availability of personnel and funds, and many other factors.

General Approach

3. Approximately 20 years ago, the WES developed a practical system (instrumentation and techniques) for relating soil strength to the mobility of military vehicles. Since then much, perhaps most, of the research and development has been done under pressure, for quick results. The research, therefore, has been more in the nature of a series of short-term programs rather than deliberate, long-term programs. Understandably, the approaches have been rather empirical where adequate theory did not exist. Many answers are at hand or can be derived, but not all with the precision that would be desirable.

4. A mass of data has now been accumulated on the strength of many kinds of soils, at many moisture contents, and under many environmental situations. The effects, not only of soils but of all relevant terrain features in the almost infinite number of combinations in which they

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exist, are beginning to be appreciated and studied. Many advances have been made in soil mechanics, soil science, and hydrology; and the electronic data processor has become a readily ava_ able tool when needed. In view of the foregoing, we feel that reevalu_ _ons of both the data and the approaches are in order.

5. More specific recommendations by the Board of Consultants are presented in the following paragraphs.

Soil Moisture

6. The Board could not fail to observe that the great majority of papers presented at the conference were concerned with only one factor pertinent to trafficability, namely soil moisture. The preponderance of moisture-oriented studies reflects the emphasis placed on this one item by WES investigators for the past 15 years.

7. In recognition of the obvious importance of soil moisture to soil strength, a system has been developed for predicting soil moisture. From the studies leading to the development of the system, much has been learned of soil moisture, its changes, and its effects on trafficability.

8. The problem of soil moisture prediction is complicated by so many variables and their interactions that it will never be completely solved. Some refinements have been made during the past eight years, but a cutoff should be made. It appears to the Board that for the sake of a well-balanced program, further routine collection of soil moisture data should be held in abeyance.

9. The soil moisture prediction system is perhaps based on too few parameters and on parameters that cannot effectively be measured at the present time. We, therefore, suggest that the program move in two directions: (a) a further study of fundamental factors influencing soil moisture, and (b) an employment of the present system for limited use under conditions defined by probabilities.

10. The development of a theoretically derived predictive equation is now highly desirable. There are very definite relations among soil classes, soil physical conditions, and soil strength. There are also

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very definite relations between soil physical characteristics and water transmission characteristics, and the latter have a significant influence on both the accretion and depletion of soil moisture.

11. We suggest that the "total soil profile" concept be utilized; all depths that furnish and receive moisture from the 6- to 12-in. layer by gravitational flow, interflow, and seepage must be accounted for. Concentration on the 6- to 12-in. layer does not lend itself to theoretical evaluation by energy balance or by water movement into and from this layer. Fundamental processes can best be examined in reference to the entire profile; once they have been worked out, a means of assessing their integrated effect on the 6- to 12-in. layer may be possible.

12. Attention must be given to wetting of the soil by rainfall as the wetting is affected particularly by the rainfall characteristics, plant canopy geometry, soil physical conditions (infiltration and drainage), and topographic conditions (subsurface flow). Other items that should be considered include the effective thickness of the capillary fringe with respect to trafficability, the soil profile characteristics (stratification, etc.), and the water table regime with respect to potential gradients, water transfer, and the influence of the river basin.

13. Close liaison with other groups conducting similar research is desirable. Personal contact with such groups will assure beneficial and complementary coordination. New contacts should be made, and those now existing should be continued. Of particular interest are the American Meteorological Society and the group at Fort Huachuca who are primarily concerned with using a meteorological approach to predicting soil moisture. NASA has made considerable progress in photo reconnaissance, having developed hardware, and is now concerned with the significance of photographs; these may be most useful for translating point measurements to items of significance and extrapolating point measurements geographically. Also of interest are the plans of the Department of Interior for launching a reconnaissance satellite; among other things, soil moisture surveillance is anticipated.

14. The Board feels that expenditures of efforts and large sums of money for devising improved moisture sensing devices would not be

advisable. There is little evidence to indicate that any moisture pre-
diction system would be greatly improved if based on highly accurate
measurements (or even exact measurements) of soil moisture content.

Soil Strength and Trafficability

15. While the soil strength data cover a wide range of soils, the
vast majority of them are in the soil strength range greater than 100
rating cone index. Above this level, soils are trafficable to practically
all military vehicles; hence, many of the data have no relevance to traf-
ficability, although they may have relevance to other military operations.
Abstention from extensive collection of data in areas of generally good
trafficability is strongly urged. There is a paucity of soil strength
data for permanently wet places like marshes and swamps; data from such
sites are needed.

16. In the interest of more rapid progress it would be desirable
to formulate programs directed specifically toward prediction of traf-
ficability rather than toward prediction of isolated individual factors
such as moisture or water table elevation. The same measurement effort
could be made to measure the trafficability parameters directly. A system
for estimating trafficability directly, the soil trafficability classifica-
tion system, appears to be workable and of immediate usefulness.

17. The soil moisture-strength prediction system should be field
tested in an exercise similar to that conducted at Ft. Campbell in 1954.
The soil trafficability classification system should be tested at the same
time to serve as a check on the reliability of the system.

18. The present knowledge of soil trafficability prediction should
be condensed into a simple and practical procedural form and published as
a technical report.

19. The soil trafficability conditions are defined only in terms
of the rating cone index of the 6- to 12-in. soil layer. The Board feels
that this concept merits reexamination. It restricts the usefulness of
results to those operations that involve 40 or 50 vehicles moving in trace.
The trafficability prediction systems need to be expanded in order that

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they may be applicable to 1-, 2-, or 50-pass situations. Also, the Board recommends that factors such as horizontal resistance, surface friction (slipperiness), sidewall drag in rut, and microgeometry be considered quantitatively in terms of their effects on vehicle mobility.

Variation

20. Variation, as noted in the presentation on soil variability, constitutes a very real problem. Without an adequate determination of the variation (whether due to instrumentation, technique, or soil variability) inherent in the test procedures followed, a decision as to whether or not differences between test sites are real cannot be made.

21. Attempts should be made to establish the size of soil inclusions which effectively influence soil trafficability. Procedures should also be established for the recognition and delineation of such anomalous areas, particularly if the anomalies are primarily subsurface in nature.

22. The variability of penetrometer readings due to operator error, the variability due to soil differences, and the variability of rainfall predictions are all of importance; if significant, they must be accommodated in the soil trafficability prediction system. In view of these variabilities, it seems unrealistic to strive for high degrees of prediction accuracy if results are to be applied to areas and not to just one point in space.

Procedures for Presenting Data

23. The various presentations were complicated by the fact that differing units of measurement (e.g., moisture content presented in inches and percent weight), graphing methods, etc., were used. It is recommended that all such procedures be standarized when possible.

24. When the accuracy of prediction is characterized by moisture content deviations, the deviations should be expressed in terms of relative moisture change, i.e., $\Delta w/w$.

Plans for the Future

25. The Board has considered the proposed "Plans for the Future" and concurs with the proposition that further studies be undertaken with a view toward applicability of results under battlefield environmental conditions.

26. It is suggested that a revised proposal for future programming be prepared and that, in the preparation, the views of the Board expressed above be duly considered.

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APPENDIX A: METHODS OF SOIL MOISTURE PREDICTION FOR
TRAFFICABILITY PURPOSES

by

C. A. Carlson

CONTENTS

PART I: DERIVATION OF PREDICTION METHOD WITH SPECIFIC RELATIONS

Background and Purpose

1. The soil moisture prediction method was developed to predict, on
a daily basis, the net moisture content of the 6- to 12-in.* soil layer, the
critical layer for most military vehicles. Concurrent predictions are made
for the 0- to 6-in. layer also, since it is necessary to route water from
rainfall through the surface layer into the critical layer. Requirements
for the prediction method include simplicity, to permit use by nontechnical
personnel, and availability of data needed to make a prediction. The data
may come from published sources or from reports from the field.

2. Although many factors of soil, weather, topography, and vegetation
influence the moisture changes in a soil layer, it was desired to select the
dominant expressions of change, particularly those that integrate the in-
fluence of several factors, to achieve simplicity yet maintain a useful
level of accuracy. It was found in early studies that the influence of
individual factors generally could not be ascertained from the data. Indi-
vidual effects were masked by the varied effects of many variables, some
of which were not measured, and the change generated by all variables was
often small, less than the variability of the day-to-day moisture measure-
ments. The requirement for prediction of net moisture content in surface
layers made it unnecessary to account for all water, such as runoff or that
distributed throughout a root zone or soil profile.

Development

3. The soil moisture prediction method was developed empirically
from daily measurements made in the field. At the start, three test sites
were established near Vicksburg. These were instrumented with fiber glass
electrical-resistance moisture units spaced at 3-in. depths and with

weather instruments for measuring rainfall, air temperature, humidity, wind velocity, and pan evaporation. For bottomland sites, water table depth and stream height were also measured daily. The soil was sampled for analysis of physical properties, and periodic strength measurements were made to establish the relation between moisture content and strength. Observations of vegetative development were made.

4. The graph of moisture content versus time revealed a consistent pattern of moisture fluctuations (fig. 1). The moisture content in the layers near the surface jumped up on days with rain, and went down at a decreasing rate during interrain periods. The fluctuations for a given soil were confined between high and low moisture content levels. These characteristics of the soil moisture record are the basis of the moisture prediction method.

5. The high moisture level is called the field maximum moisture content. It is the recurring maximum moisture content of a soil layer in its natural position. It is determined by selecting the recurring peak value of moisture content from the moisture record, and represents the maximum moisture content within a day after rain. The low moisture level is called the field minimum moisture content. It is the recurring minimum moisture content of a soil layer in its natural position and is likewise selected from the moisture record.

6. Moisture loss from a soil layer is called "depletion"; it is caused by evapotranspiration and drainage. No attempt is made to distinguish between the separate effects of these processes, since the net change in moisture content is of primary interest. Examination of the moisture record of a particular site shows that the summer and winter rates of loss in the interrain periods are quite different, but within a season they are quite similar. The interrain portions of the record within a season are traced off as a family of curve segments, and a smooth curve, called the depletion curve, is drawn through the family (fig. 2). Depletion curves are derived by seasons, winter, summer, and transition (with the spring and autumn seasons grouped together to form the transition), so that three curves are needed for each layer. The two ends of the summer depletion curve represent the field maximum and minimum soil moisture contents.

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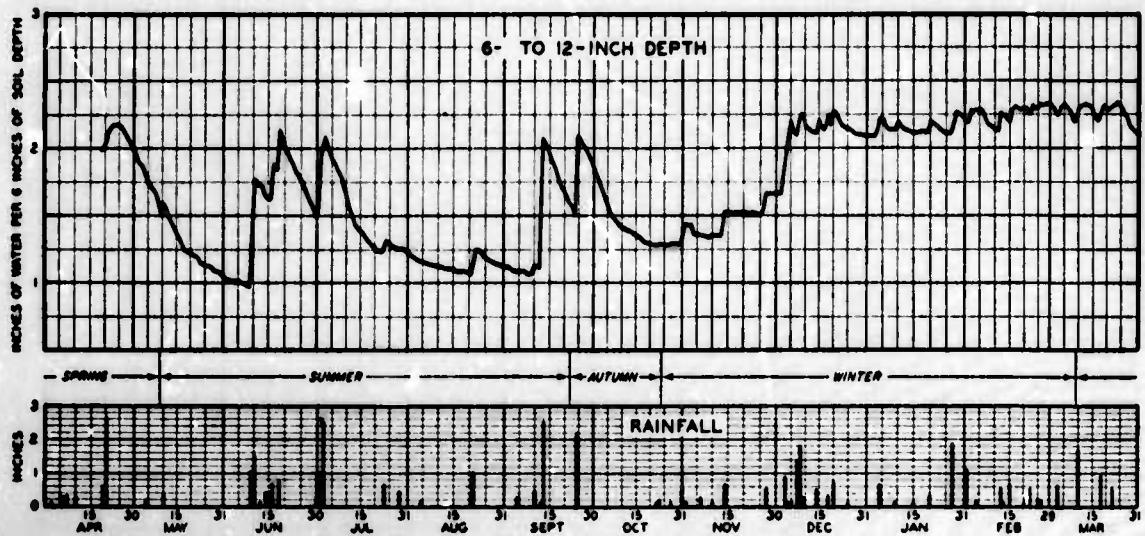
Fig. 1. Daily soil moisture record for Commerce silty clay at Mound, La., 1951-1952.
Rainfall record collected from rain gage at the site
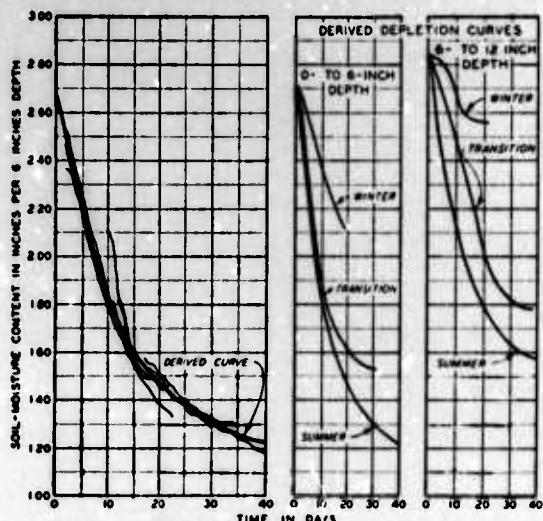
Fig. 2. Left: Derivation of a typical
depletion curve from a family of eight
actual summer depletion curves. Right:
Seasonal depletion curves. Commerce
silty clay
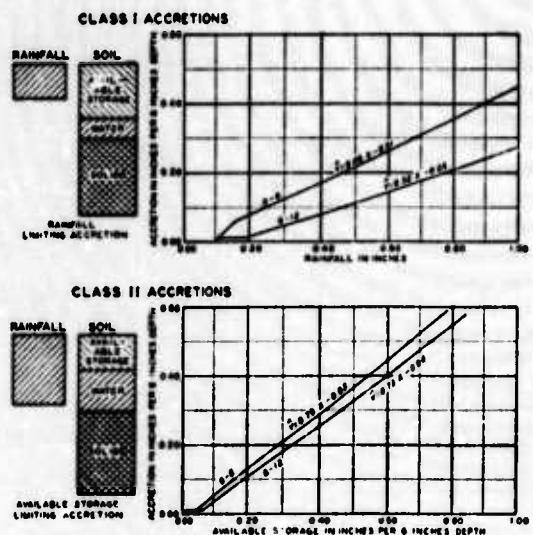
Fig. 3. Typical regressions for Class
I and Class II accretions. Commerce
silty clay

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7. It is necessary to know the dates when one season ends and the next begins, in order to know which seasonal depletion curve to use. The dates, called "transition dates," are selected from the moisture record.

8. The gain in moisture content is called "accretion." It occurs with rainfall, but studies showed that a second major factor also governed the net gain. This was the amount of space in the soil layer that could take up more water, and is called "available storage." It is the numerical difference between the field maximum moisture content and the moisture content of the soil layer before rainfall. Accretion is divided into two classes: Class I when rainfall is less than available storage, and Class II when rainfall is equal to or greater than available storage. The classification is made considering the combined available storage of the two 6-in. layers (fig. 3). Following classification, the accretions are treated separately by layers for each class. In Class I, accretion is related to rainfall, in Class II, to available storage by means of linear regressions. Averages of accretion data for small rainfalls showed that a net loss occurred rather than a gain. A minimum storm was established, usually at 0.10 in., and days on which smaller amounts fell were treated as depletion days.

Application

9. To make a prediction, the starting moisture contents and the rainfall record must be known along with the prediction relations, that is, the accretion and depletion curves, the field maximum and minimum values, minimum storm, and transition dates. With this information in hand, the prediction is a simple bookkeeping system, adding water on rainfall days using accretion relations to determine the amounts to add, and subtracting water on days with no rain, by amounts interpolated from the depletion curves.

10. The method worked for the sites at Vicksburg, each site having separately derived prediction relations. Sites were then established at many locations throughout the United States, including Alaska and Hawaii, and in Puerto Rico, the Canal Zone, and other places, in cooperation with

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various agencies and universities, particularly the U. S. Forest Service. The method worked for these varied locations, again each site having its individually derived relations.

11. Predictions made during the year of record from which the accretion and depletion relations were derived for 126 sites gave an average deviation between predicted and measured moisture contents of +0.10 in. of water per 6-in. soil layer, about +1.5 percent moisture content by weight.

Prediction Relations for Other Influencing Factors

Water table

12. On occasion, additions or changes were made in the prediction relations at a specific site to account for a soil-water influence not covered in the relations given above. A water table persisting near the soil surface posed a problem in the initial study at Vicksburg. Two of the three sites had water tables that fluctuated near the soil surface during the winter season. At one site, Rifle, the water table drained quickly. Any drainage effect was incorporated into the depletion curves, and a prediction was made continuously throughout the record with reasonable accuracy. At the second water table site, Mound, the water table did not drain quickly. Occasionally the water table remained near the ground surface for some days after rainfall and depletion did not occur during these periods. To make a prediction, the water table record was followed as well as the rainfall record, and when the water table persisted in the surface-to-12-in. layer, depletion was suspended and the moisture content was maintained at the maximum. The need for relations in the prediction method to account for influencing water tables was obvious.

13. In the second year, water table relations were developed for the Durden site at U. S. Army Engineer Waterways Experiment Station (WES), but these relations were dependent on the changing level of an adjacent pond and could not be adapted for general application, for example, to the Mound site with no pond. Another approach was tried for the initial Crossett study sites and others. For these sites the depletion curves

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were flattened at the wet end for the average number of days that the
water table persisted on occasion in the surface-to-12-in. layer. This
modification helped the prediction during winter and spring, but generated
large depletion errors in the summer when the soil wet to the maximum
without a persisting water table. These flattened curves were not used in
subsequent correlation studies of depletion.

14. In the initial Puerto Rico study, another approach was used for
a perched water table site. After the field maximum was reached, the mois-
ture content was maintained with no depletion as long as the accumulative
rainfall for 3 preceding days exceeded 2.50 in. This modification depended
on the storage-drainage characteristics of the particular site and could
not be adapted for general use. Although water table relations were incor-
porated in the prediction method as need demanded for particular sites, no
systematic treatment for general application and incorporation in the pre-
diction method has been formulated. Recent work on water table relations
will be given in a later presentation.

Designation of seasons

15. Another change found necessary in the prediction relations was
the designation of seasons for depletion curves. Usually, in the temperate
climates three seasons were used: summer, winter, and transition, which
combined spring and autumn. For northern Florida and California sites,
only two seasons were discernible from the record. At tropical sites in
an insular climate, such as Puerto Rico and elsewhere in the Caribbean
area, and in Hawaii, one season for depletion was employed throughout the
year. In a recent study in Thailand, the moisture record showed two seasons
of depletion in that tropical area.

Storms less than minimum

16. Another change found necessary at some sites was the considera-
tion of storms smaller than the minimum. The summer season at Fairbanks,
Alaska, has many small rains which may occur as a light drizzle or mist
during much of the day. In the year of study, 1954, 75 days with rainfall
were recorded from May through September. On 61 of the rainfall days, the
daily amount was less than 0.15 in. The minimum storm was established from
data averages at 0.10 in. However, days with rainfall of 0.05 to 0.10 in.

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showed no measured depletion as well as no accretion, so the prediction
was made with the moisture content held constant on those days having
rainfall of 0.05 to 0.10 in. A similar situation was anticipated in tropi-
cal wet climates with many consecutive days of rain. However, predictions
with no depletion on days below the minimum storm were no better than pre-
dictions with depletion on days below the minimum for sites tested in the
initial Puerto Rico study and in Hawaii.

Transition depletion

17. Other changes in the prediction method were explored, but have
not been used in published reports. The general method employs a transi-
tion depletion curve for spring and autumn for which the rate of moisture
loss varies by moisture content but at a fixed relation, so that at any
given moisture level the rate of loss remains constant throughout the tran-
sition season. There is some basis for using a fixed transition curve as
evidenced in the rapidity of seasonal change; spring "breaks forth" with a
thaw and rapid bud opening and vegetative growth, and in autumn the effect
of frost on vegetation is sudden and severe. These events are related to
surges of air masses which have a fairly consistent annual pattern as shown
in weather records. On the other hand, gradual changes take place during
the progression of the transition season, as evidenced by continued growth
and development of vegetation in the spring, and by the differing senescence
and frost tolerance by species with cumulative effects in the autumn. Pro-
gressive change is also shown in running averages of solar radiation, air
temperature, and other weather factors. Predictions were made with progres-
sive transition depletion relations, for which the loss at a given moisture
level was proportioned between that of winter and summer as the transition
season progressed. Results for 78 sites with daily data showed no improve-
ment in terms of average deviation of the progressive compared to the fixed
transition depletion.

Influence of nonvegetated condition

18. In general, no differences could be discerned in depletion
curves resulting from differences in the vegetative cover at the test site,
such as grass compared to trees. The lack of difference was attributed
to the testing of surface layers only which had sufficient roots regardless

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of the plant species. No tests were made by root zones, for which depletion differences are known to occur. The absence of plant cover resulted in a considerable reduction in the depletion loss of the 6- to 12-in. layer, but little change in the surface to 6-in. layer. The differences were shown in bared versus vegetated sites at various places in the United States and in a cultivation test at Vicksburg. Predictions for cultivated areas would require a change in depletion rates during the time that the area is bare, such as from plowing until the crop is fully established, for which canopy closure may be an index.

Influence of frost and thaw

19. Limited studies have been made of the influence of the frost period and eventual thaw. The freezing concentrates water as ice in lenses and grains which, upon thawing, results in a decrease in density of the surface layers, an increase in water content above the usual field maximum moisture content of the summer condition, and a low strength. The tests showed that the effect may be of short duration, lasting a week or so, but during this time strength can be critical. Where applicable, the prediction method needs to account for the thaw influence.

PART II: TENTATIVE AVERAGE MOISTURE PREDICTION RELATIONS

Approach

20. The prediction relations described thus far were derived from specific sites and apply only to these sites or strictly analogous ones and therefore have a limited utility. Average prediction relations were desired for application to areas without detailed records. A basis was needed for grouping values for averaging and then for selecting a set of relations from the averages for application to an area. The basis for averaging may be by soil, climate, topography, or other means, and it follows that knowledge of these characteristics for the area in question must be available in order to make proper selections from the averages. Correlation studies were made among the sets of prediction relations and site characteristics for the sites available through 1954, and a set of tentative average relations was derived for testing. The data were limited, so that many characteristics were not evaluated. Nevertheless, the derivation and application of an interim set of average relations were considered worthwhile because such a set would serve three purposes:

    a. It would show the possibilities of a general moisture prediction system and if found sufficiently accurate, the system, could be used immediately, if needed, pending a subsequent improved set of average relations.

    b. It would point out conditions, not covered by the prediction development sites, needing further measurement and study to improve accuracy of the prediction system.

    c. It might show that the average prediction relations could be adjusted and modified to fit requirements of specific regions or conditions to improve prediction accuracy without further measurement.

Derivations of Average Prediction Relations

Field maximum moisture content

21. Data from 39 sites were used in the evaluation of field maximum. Various characteristics of the soil and site were correlated with the field maximum values by graphical and numerical means for each 6-in. layer. Five factors were selected for use, including sand, clay, and

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organic contents, moisture content at the 0.06-atm soil moisture tension, and wetness index. The soil factors need no explanation. The wetness index was devised for this study to evaluate the influence of site characteristics on the potential maximum moisture content. Sites were classified by wetness index considering two factors, the maximum height of the water table as measured in a well at the site, and the depth of wetting by rainfall. The classification is given in table A1. Wetness index 2 represents the well-drained site of the humid region that is wetted to a depth greater than 4 ft; wetness index 4 represents the waterlogged site. It should be pointed out that the index is not a classification of water tables since it does not consider durations or fluctuations of the water table, but only considers the maximum wetting from rainfall or water tables.

22. Equations were derived for approximating the field maximum from the five factors using the multiple regression technique. The 0.06-atm soil moisture tension value correlated best as a single factor. Multiple factor equations were derived with and without soil moisture tension since measurements of this factor are not widely available. The equations follow:

0- to 6-in. Layer	Coefficient of Determination
$Max = -0.31 + 1.042\ T$	0.73
$Max = 2.06 - 0.011\ S + 0.116\ OM + 0.151\ WI$	0.69
$Max = 0.68 - 0.006\ S + 0.077\ WI + 0.737\ T$	0.81

6- to 12-in. Layer	
$Max = 0.20 + 0.897\ T$	0.63
$Max = 2.06 - 0.012\ S + 0.008\ C + 0.155\ WI$	0.63
$Max = 0.83 - 0.006\ S + 0.007\ C + 0.134\ WI + 0.492\ T$	0.79

Where:

  S = percent sand

  C = percent clay

  OM = percent organic matter content

  WI = wetness index

  T = moisture content, in. per 6 in. of soil, at 0.06-atm tension

Field minimum moisture content

23. The averaging for field minimum moisture content followed the procedures used for field maximum. Multiple regression equations were derived from data on 59 sites using the factors of clay and organic contents and wetness index. The 15-atm moisture tension value, which approximates the wilting point, would have contributed in the equations but was not used since limited data were available at the time. The equations follow:

$$\underline{\text{0- to 6-in. Layer}}$$
$$\text{Min} = -0.013 + 0.007\ C + 0.074\ OM + 0.149\ WI$$

$$\underline{\text{6- to 12-in. Layer}}$$
$$\text{Min} = 0.131 + 0.017\ C + 0.044\ OM + 0.119\ WI$$

Where:

    C = percent sand

  OM = percent organic matter content

  WI = wetness index

Depletion relations

24. The averaging of depletion relations was done using data on 48 sites. The relations expressed as curves of moisture content versus time had a variety of shapes and durations, reflecting differences in rates of evapotranspiration and drainage as the moisture level decreased. The correlation of these curves presented a problem. No simple mathematical expression was found that would fit the majority of the curves to provide coefficients that could be correlated with soil and site factors. By assembling curves into families, gross differences were discerned by soil textural groups; sandy, silty, and clayey soils. Subgrouping by other factors could not be done because there were too few sites in a group. For example, the clay group had only three sites in the 0- to 6-in. layer and only eight sites in the 6- to 12-in. layer, with many sites occurring in upland positions in the South. Averages of moisture loss from the field maximum were calculated at time intervals, 1-, 5-, 10-days, etc., for each textural group by season and soil layer, as shown in fig. 4. The average curves were initiated at the average field maximum and ended after
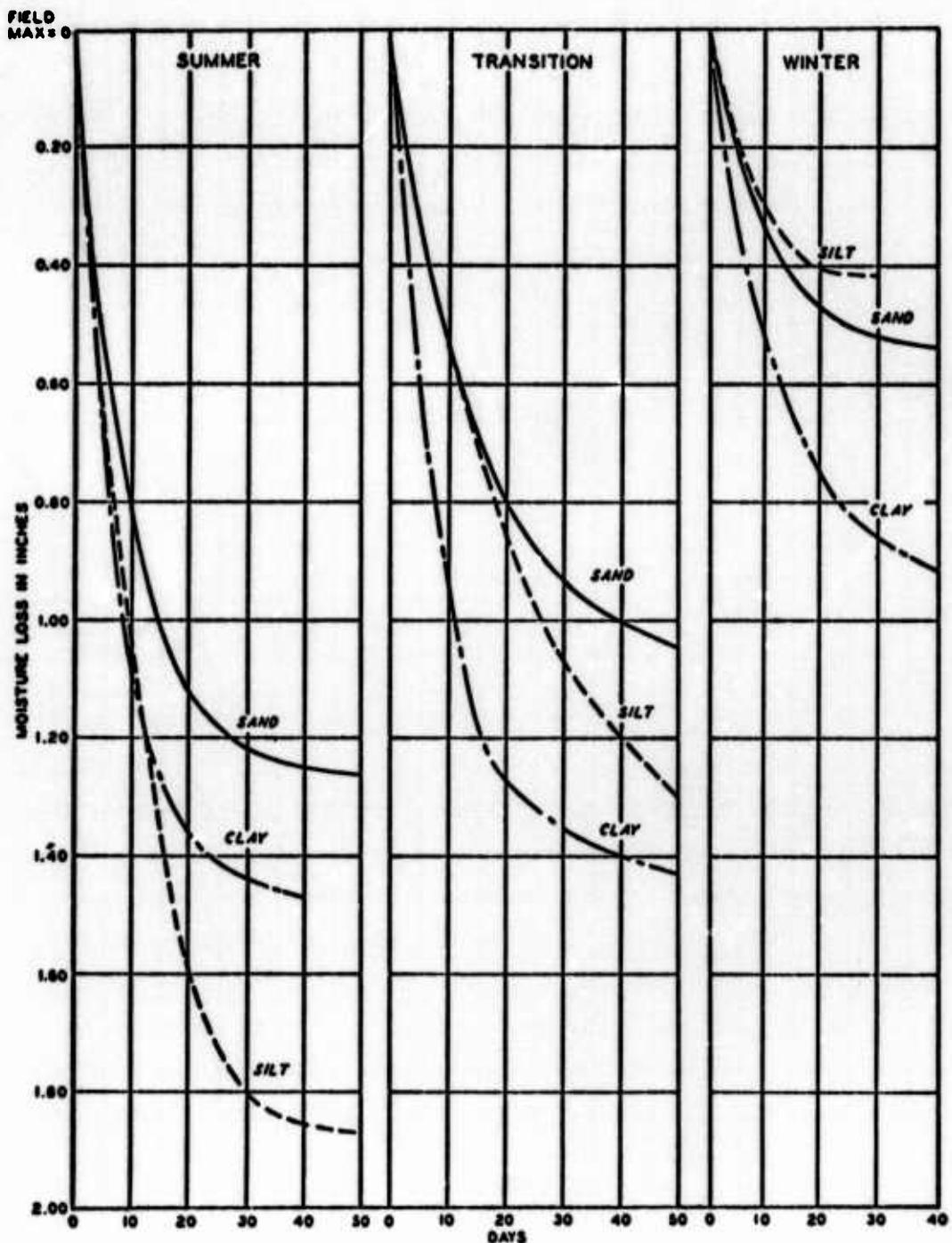
Fig. 4a. Curves showing average moisture loss from field maximum,
by seasons and textural groups, in surface to 6-in. layer

A12
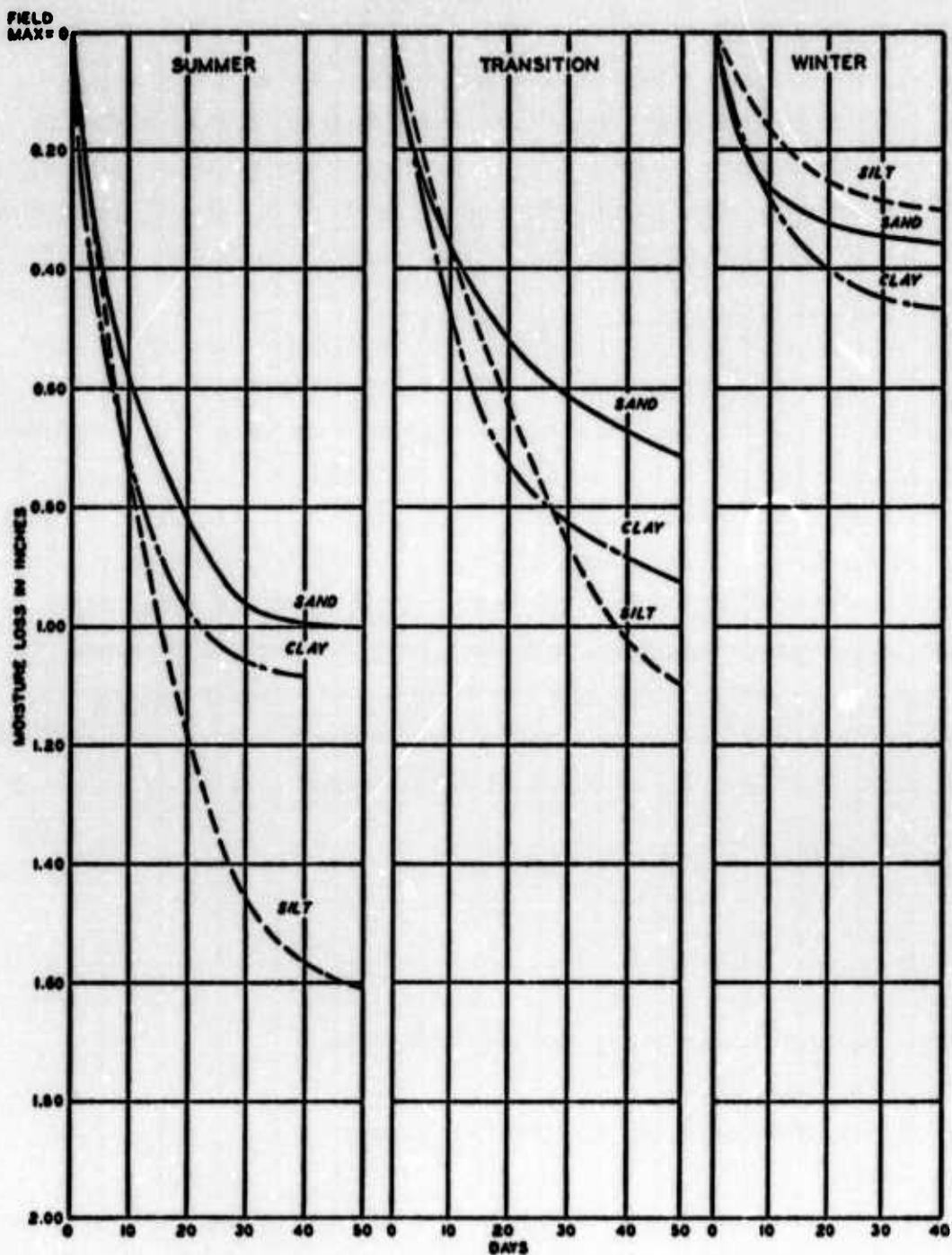
Fig. 4b. Curves showing average moisture loss from field maximum, by seasons and textural groups, in 6- to 12-in. layer

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a period of 40 or 50 days at an average minimum of those curves that extended to this time. Few sites had the average field maximum or the average range between maximum or minimum. Thus, in order to use the average curves on sites with differing field maxima and ranges, two assumptions had to be made: (a) that the average depletion curve could be shifted higher or lower to fit an estimated field maximum, and (b) that a curve could be prorated over a greater or lesser range. For use in prediction, average depletion curves are adjusted to fit estimated field maximum and minimum values.

Accretion relations

25. Accretion relations were derived as linear regressions which provided values of slope and intercept that were amenable to correlation with soil and site factors. Unfortunately, no correlations were apparent; any grouping showed a variety of slopes. Multiple regressions were made using individual values of accretion against rainfall, available storage, and various soil and site factors. These showed no correlation except with rainfall and available storage, the original accretion factors. The gross textural groupings, sand, silt, and clay, used for depletion showed no differentiation between accretion regressions. So average regressions were calculated from data on all available sites, 75 sites for class I and 54 sites for class II. The average regressions follow:

Class	0- to 6-in. Layer	6- to 12-in. Layer
I	$Y = 0.47X - 0.01$	$Y = 0.22X - 0.01$
II	$Y = 0.75Z - 0.05$	$Y = 0.60Z - 0.02$

Where:

Y = estimated accretion, in. per 6-in. layer

X = rainfall, in.

Z = available storage, in. per 6-in. layer

Minimum storm

26. The minimum storm was determined for 106 sites. The size of the minimum storm varied directly with the density of vegetation to some extent. This was expected since denser vegetation would provide greater interception, requiring more rainfall before the soil was wetted. However, 89 sites, including 16 bare and 31 forested, had a minimum storm of 0.10 in.

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Therefore, this value is generally used with the tentative average relations.

Transition dates

27. A method for selecting transition dates was not devised for the average relations. The values determined for the prediction development sites were tabulated for use as a guide in selecting dates and were supplemented by knowledge of the test sites being predicted.

Other factors

28. No average method for identification of or allowance for persisting water tables was devised. Predictions were made at sites with water tables as though none was present. Bared or plowed areas were predicted as though fully vegetated; however, test sites as a rule were located on noncultivated land. The designation of seasons and allowance for storms smaller than the minimum size were modified on the basis of findings in the area or by trial.

Use of the Tentative Average Relations

29. A prediction is made with average relations by means of the same procedures discussed earlier for specific relations derived for a particular site. The same computer program is used except for modifying values for accretion, depletion, field maximum and minimum, and on occasion season and minimum storm.

30. A direct check of the tentative average relations was made with 24 sites used in the derivation of the average relations, giving average deviations for predicted minus measured values of 0.13 in. and 0.09 in. for the specific relations, and 0.26 in. and 0.23 in. for the tentative average relations in the 0- to 6- and 6- to 12-in. layers, respectively. The deviations are roughly equivalent to ±1.5 percent moisture content by weight for the specific, and ±3 percent for the average relations.

31. The average relations were tested further on 601 sites located in four regions of the United States. Rainfall records were obtained from the nearest official weather station which was located from 1 to 5 miles away from the site. Predictions were compared with results of gravimetric

moisture samples taken at monthly intervals. Average deviations were
0.33 in. and 0.31 in. for the 0- to 6-in. and 6- to 12-in. layers. Sites
with water tables, with organic content above 4 percent, or with clay
soil had the greatest deviations, indicating that the average relations
needed improvement to account for these conditions.

32. The tentative average relations were tested next on the data
of the initial Puerto Rico study conducted during 1955-56. Average
deviations of 0.38 in. and 0.39 in. resulted for the two 6-in. layers,
equivalent to about +4.7 percent moisture content by weight. The major
source of error resulted from differences in shape of depletion curves and
in the field maximum and minimum values which terminated the curves. The
need for improving the tentative average relations was obvious, and con-
siderable effort was expended to improve them. Work centered on equations
for field maximum and minimum values, mathematical fitting and correlation
of depletion relations, and exploring methods for estimating transition
dates. The plan and intent were the development of improved average
relations for testing with the subsequent study in Hawaii. Unfortunately
results were largely negative; no improvements in average relations were
accomplished, although some results were obtained. Equations for field
maximum and minimum were derived in terms of soil plasticity, fines, and
other factors, but the accuracy was the same as equations with sand, clay,
etc., for sites in the United States and Puerto Rico. An excellent
mathematical fit was found for the varied shapes of depletion curves using
the hyperbola with the moisture-time coordinates expressed as logarithms.
The coefficients did not correlate well with soil and site factors, so a
systematic set of relations could not be derived. Factors and methods
for estimating transition dates were explored in detail, but no single
method was established for use. Work to improve the average relations
practically ceased by 1962.

33. Some applications of the prediction method with tentative average
relations have been made which demonstrated their usefulness. In a study
by Campbell and Rich of the U. S. Forest Service, moisture prediction
proved to be superior to rainfall amounts in correlating grass growth both
within and between years. In a study by Bassett of the U. S. Forest

Service, the moisture prediction was utilized to calculate indexes of
potential growth which correlated highly with measured pine timber growth.
The method was adapted by the U. S. Naval Radiological Defense Laboratory
for use in the prediction of induced activity.

Table A1

Classification of Sites by Wetness Index

Wetness Index	Potential Wetness	Depth to Water Table	Depth of Wetting	General Characteristics of Sites*
0	Arid	Indeterminable	Less than 1 ft	Located in desert regions
1	Dry	Indeterminable	1-4 ft	Steeply sloping, denuded, or severely eroded and gullied. Mostly semiarid to arid regions
2	Average	More than 4 ft	More than 4 ft	Well-drained soil with no restricted layers or pans; fair to good internal and external drainage. Slope may be flat to steep
3	Wet	1-4 ft	To water table	Soil not well drained. Restricted layers or deep pans may be present. May occur at base of slopes, on terraces, upland flats, or bottomlands
4	Saturated	Less than 1 ft	To water table	Sites waterlogged or flooded at least part of year. Bottomlands subject to frequent overflow. Upland flats with poor internal drainage or shallow pans. Slopes with very poor internal drainage

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* For use in classification when water table and wetting depths are not measured.

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APPENDIX B: EFFECTS AND DEFICIENCIES OF FACTORS USED IN
WES SOIL MOISTURE PREDICTION SYSTEM

by

A. R. McDaniel

Contents

APPENDIX B: EFFECTS AND DEFICIENCIES OF FACTORS USED IN
WES SOIL MOISTURE PREDICTION SYSTEM

Introduction

1. The accuracy of predicting soil moisture by the Waterways Experiment Station (WES) method is dependent upon the accuracy of the factors used in the method. These factors are: (a) initial moisture content, (b) field maximum moisture content, (c) field minimum moisture content, (d) minimum size storm, (e) daily rainfall, (f) accretion relations, and (g) depletion relations. Specific and average factors are used. Specific factors are those developed from data collected at a particular (specific) site and are used for predictions at that site. Average factors are the average of specific factors from several sites and are used for predictions at sites where the specific factors are not known.

2. A comparison of predicted and measured moisture contents has shown average deviations of ± 0.08 and ± 0.35 in. per 6-in. soil layer (± 6 and ± 27 percent of the soil moisture range between field maximum and minimum moisture content) for specific and average factor predictions, respectively, when measured rainfall is used. Because deviations smaller than these are desired and in some cases required for certain military planning purposes, a continuous effort is being directed toward improving the accuracy of predictions. As part of this effort each of the prediction factors has been examined in detail. The purpose of this paper is to examine the effects of each factor on the overall accuracy of the system and to point out some deficiencies which were uncovered during this examination. Ideally the effect of each factor is best examined by holding all other factors constant while varying the one of interest. To the maximum extent feasible, this was done. Suggestions for improving some of the factors are also given.

Prediction Factor Deficiencies

Initial moisture content

3. The use of an erroneous initial moisture content in the

prediction system will result in an error in the predicted moisture content. The amount of this error will diminish daily for a period ranging from 1 to 60 days until the error no longer exists. The length of the period depends mainly on the amount of error in the initial moisture content and the distribution and amount of rainfall. The effects of these conditions are illustrated in fig. 1. Moisture predictions are shown for four different hypothetical cases. Two predictions were made for each test, one with a high and the other with a low starting moisture content; all other factors were kept constant. In the four cases the predicted and actual moisture contents merged after a period ranging from 8 to 47 days. This suggests that if accurate predictions are desired during the first few days, the initial moisture content should be accurate; and further, that if accurate predictions are desired beyond 50 days the initial moisture content need not be accurate.

Field maximum and field
minimum moisture contents

4. It is not possible to vary either field maximum or field minimum moisture contents and simultaneously keep depletion curves unchanged. In order to arrive at an estimate of the effects of these factors on the march of moisture, it was decided to change both values the same amount in the same direction simultaneously. In fig. 2 the solid line (curve 1) represents a hypothetical "accurate" march of moisture based on the rainfall pattern shown. The dashed line (curve 2) indicates the path that the moisture content prediction would take if the maximum and minimum values were each increased by 0.3 in. The shape of the depletion curve and all other pertinent factors were retained constant. While it is not possible to specify exact effects of the "erroneous" field maximum and minimum values (since these would vary with specific situations) it is obvious that an error in field maximum and minimum values will produce a significant error in the predicted moisture content values.

5. For specific sites, the field maximum and the field minimum moisture contents are derived from measured data and therefore are
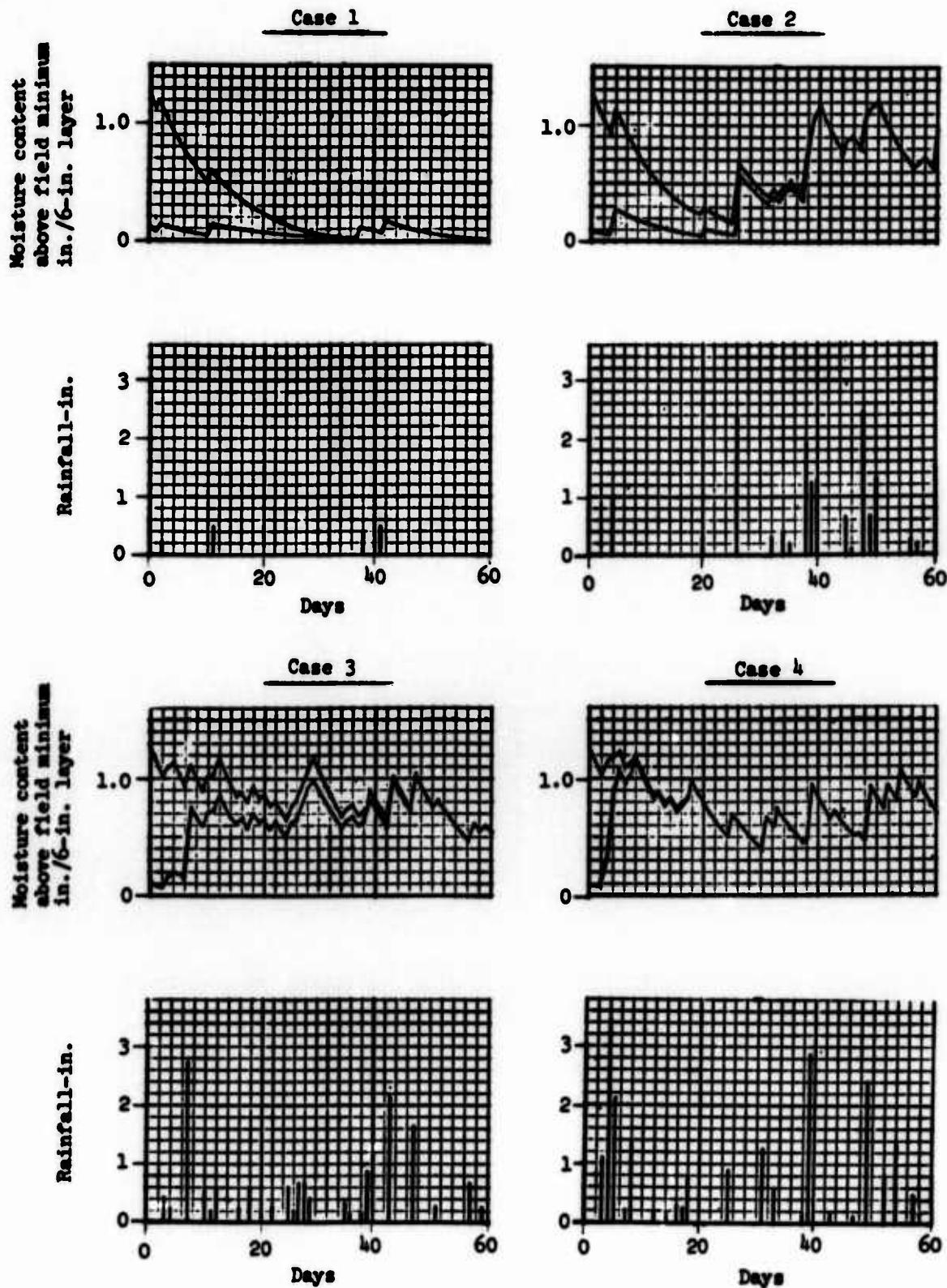
Fig. 1. Rainfall and predicted moisture content

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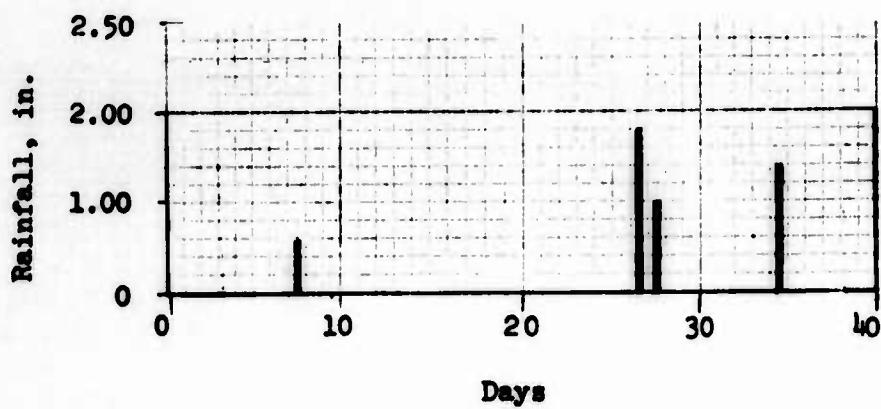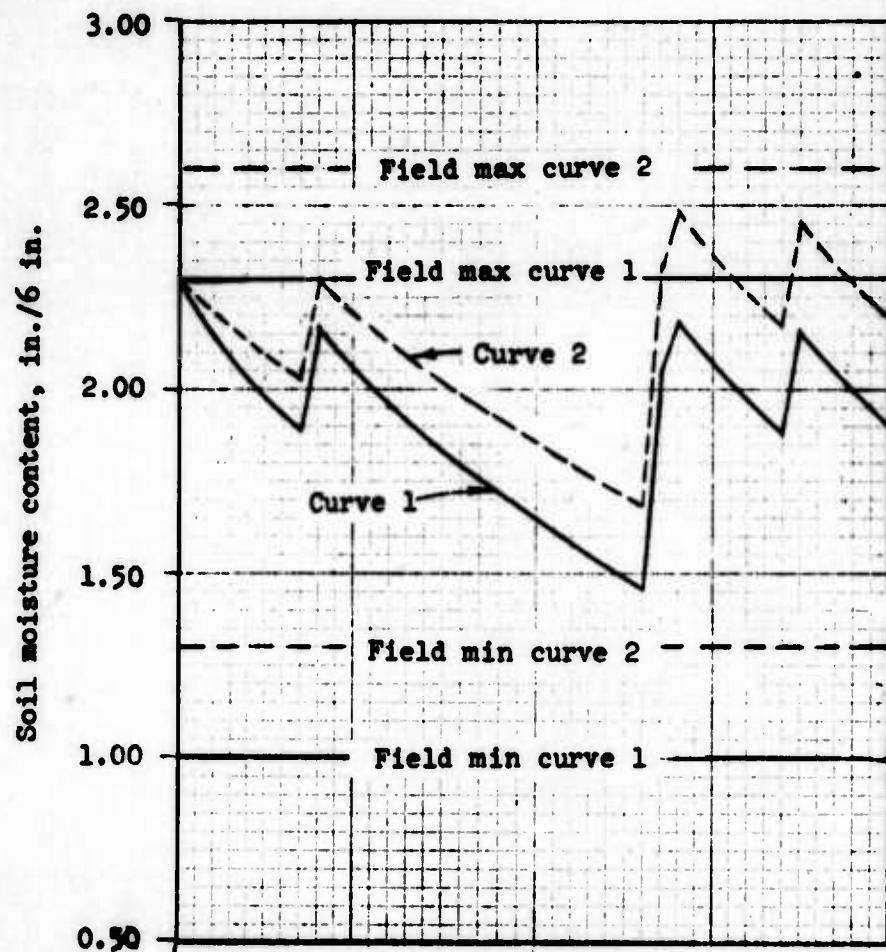
Fig. 2. Effect of shift in field maximum and field
minimum with other factors constant

usually accurate. For other sites these factors must be estimated. Equations have been developed for estimating these factors from a knowledge of the percent sand, silt, clay, and organic matter; moisture content at 0.06-atm tension of the soil; and site wetness characteristics (expressed as wetness index). The equations developed using these properties explained only about 80 percent of the variation of the two factors; therefore, they would probably not be very accurate when applied to soils at sites other than those from which they were developed. This was found to be true when they were applied to soils in Mississippi and Oregon. The mean absolute deviations between measured and estimated field maximum and field minimum moisture contents for the 6- to 12-in. soil layer were 0.18 and 0.10 in., respectively. When applied to soils in Colombia, Costa Rica, and Panama, the deviations were 0.71 and 0.83 in. for field maximum and field minimum moisture contents, respectively. This indicates that these equations need to be revised if more accurate predictions are desired. Because the equations require knowledge of soil properties often more difficult to obtain or estimate than the field maximum and field minimum moisture contents, consideration should be given to the possibility of developing new equations with properties that can easily be obtained from maps or by remote means.

Minimum size storm

6. The minimum size storm is the smallest daily rainfall amount used in moisture prediction for a particular soil-vegetation condition. Smaller storms do not appreciably wet the soil, and normal depletion occurs. If detailed rainfall and soil moisture content data are available for a site, the minimum size storm can be easily determined; otherwise, the value is usually estimated to be 0.10 in. The influence of the value used depends upon the number of storms with amounts close to the minimum size, because a small error in estimating this size could result in a predicted depletion when accretion actually occurred, or vice versa.

7. Fig. 3 illustrates the effect of an erroneous estimation of the minimum size storm. The rains occurring on days 4, 5, 7, 8, 19, and 20 result in predicted accretions if a minimum size storm value of 0.05 in. is used; depletions are predicted if a value of 0.10 in. is used. At Panama

B5
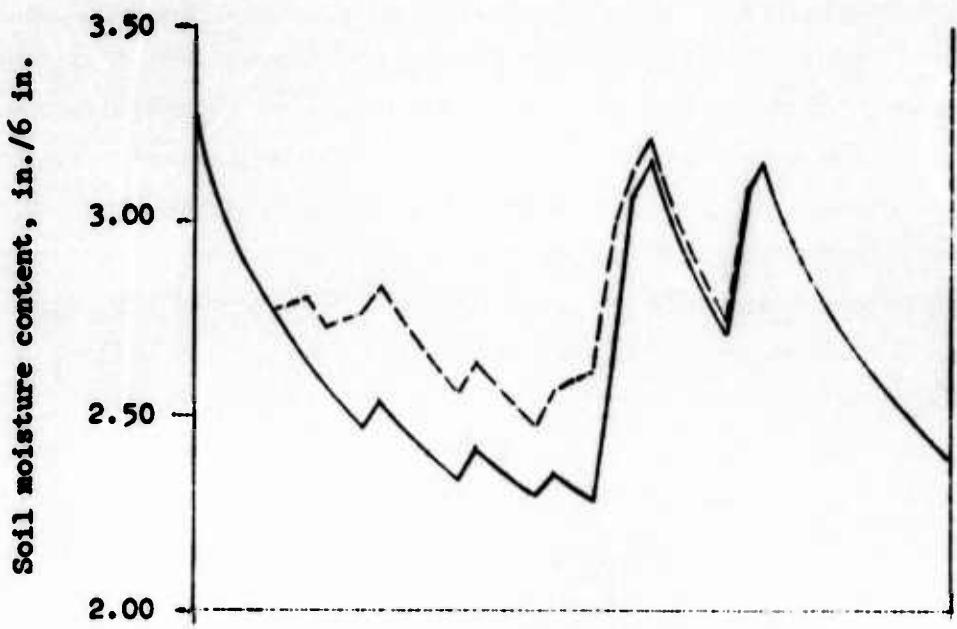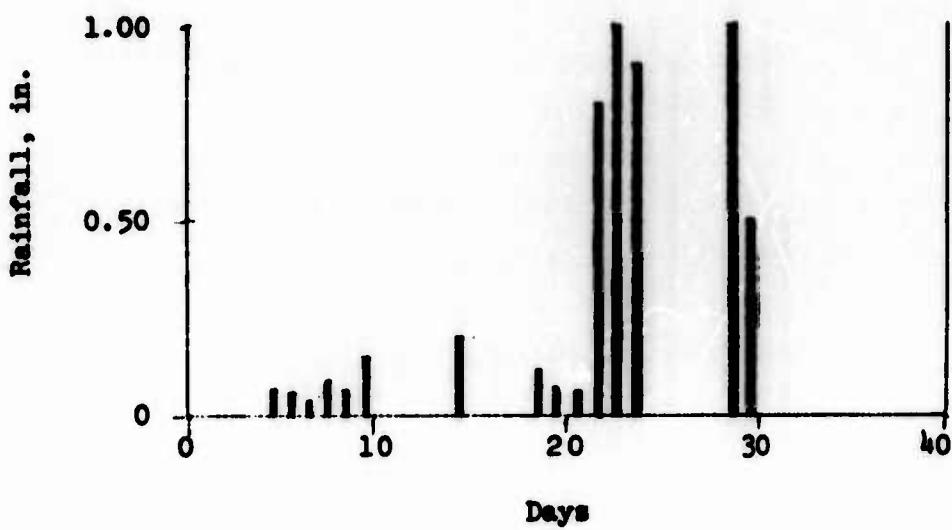
Fig. 3. The effect of minimum size storm
on predicted soil moisture content

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site 202 in 1962, rainfalls for 53 of 153 storms were less than 0.15 in.; this demonstrates the need for accurate determinations of minimum size storm values.

Daily rainfall

8. The accuracy of the prediction of soil moisture content depends directly on the accuracy of the determination of the amount of rain that falls on a site in a given 24-hr period. Fig. 4 illustrates the errors that can occur in predicted soil moisture contents directly attributable to differences in predicted rainfall amounts. The magnitudes of the errors are dependent upon the rainfall amounts and whether the rainfalls are considered to fall in the class I or class II storm categories (see paragraphs 10 and 11). In general, however, errors in predicted soil moisture contents will be in the same direction as are the errors in predicted rainfalls.

9. No published data were found that state the accuracy with which rainfall can be forecast; however, it is generally well known that the state-of-the-art of rainfall forecasting is far from good, especially with respect to predictions of rainfall amounts. At the present time, predictions of moisture content, using the WES prediction system, are more valid than predictions of rainfall amount. From this viewpoint, at least, the WES system, with all its imperfections, appears to be satisfactory.

Accretion relations

10. The accretion of soil moisture depends on rainfall and available storage. The following equations are used for predictions:

$$\text{Class I, } Y = a + bX$$

$$\text{Class II, } Y = a + bZ$$

where:

    Y = amount of accretion

    a and b = constants

    X = amount of rainfall

    Z = available storage of the 6-in. soil layer

11. The class I equation is used when the daily rainfall is less than the available storage in the 0- to 12-in. soil layer. The class II equation is used the rest of the time. For sites where specific factors

B7
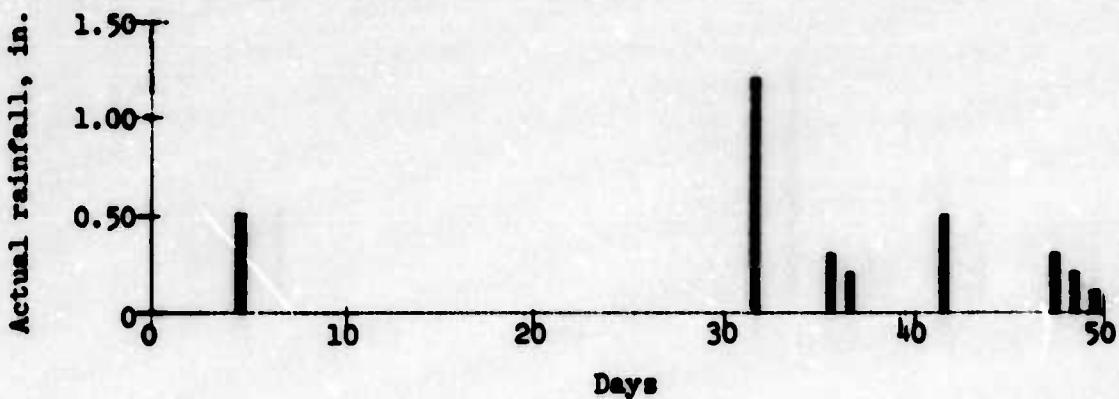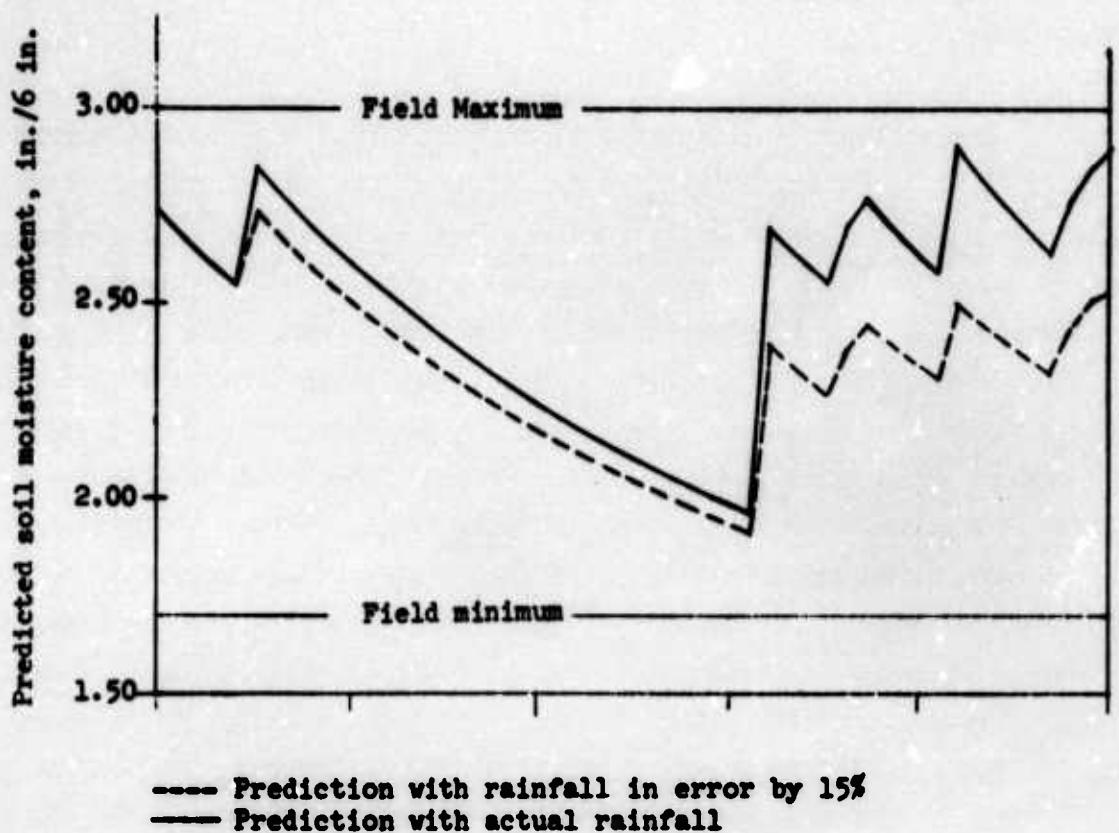
Fig. 4. The effect of erroneous rainfall values (measured or predicted) on predicted soil moisture content

are used, the constants a and b are determined from data collected at the site to which they are applied. For other sites where specific data are not available, the values of the constants a and b are averaged from data for 132 sites located in the United States (U. S.). These U. S. average constants are shown in the equations as follows:

Class	Surface to 6-in. Soil Layer	6- to 12-in. Soil Layer
I	$Y = -0.01 + 0.47X$	$Y = -0.01 + 0.22X$
II	$Y = -0.05 + 0.75Z$	$Y = -0.02 + 0.60Z$

12. Use of these equations would produce errors in predicted moisture contents if the form of the equation or the equation constants were in error. The constants, for specific sites, were derived from measured data and therefore are fairly reliable. The average constants by the nature of their derivation would be less reliable. In order to determine if the form of the equation is correct, the accretion-rainfall relation was determined for several soils using the U. S. average constants in the equations. The relations for two different tests are shown in fig. 5.

13. The figure shows no accretion below a minimum size storm, and a lack of continuity of the accretion line when progressing from class I to class II accretions. Tests of the prediction method indicated that these assumptions were incorrect and that a new equation was needed to define accretion. Accordingly a new equation was developed as follows:

$$M_2 = R - (R - M_1) e^{-kr}$$

where:

M_2 = moisture content above field minimum following the rainstorm

R = moisture content range between field maximum and minimum

M_1 = moisture content above field minimum preceding the rainstorm

e = 2.718

k = accretion constant (0.60 for U. S. average)

r = rainfall factor

Fig. 5. Accretion versus rainfall

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where:

$$r_{0 \text{ to } 6 \text{ in.}} = \frac{\text{rainfall}}{R_{0 \text{ to } 6 \text{ in.}}}$$

$$r_{6 \text{ to } 12 \text{ in.}} = \frac{\text{rainfall} - (M_2 - M_1)_{0 \text{ to } 6 \text{ in.}}}{R_{6 \text{ to } 12 \text{ in.}}}$$

14. The new and old equations are shown graphically in fig. 6. The new equation has been used on sites in Costa Rica and indications are that it provides more accurate moisture predictions than the old equation.
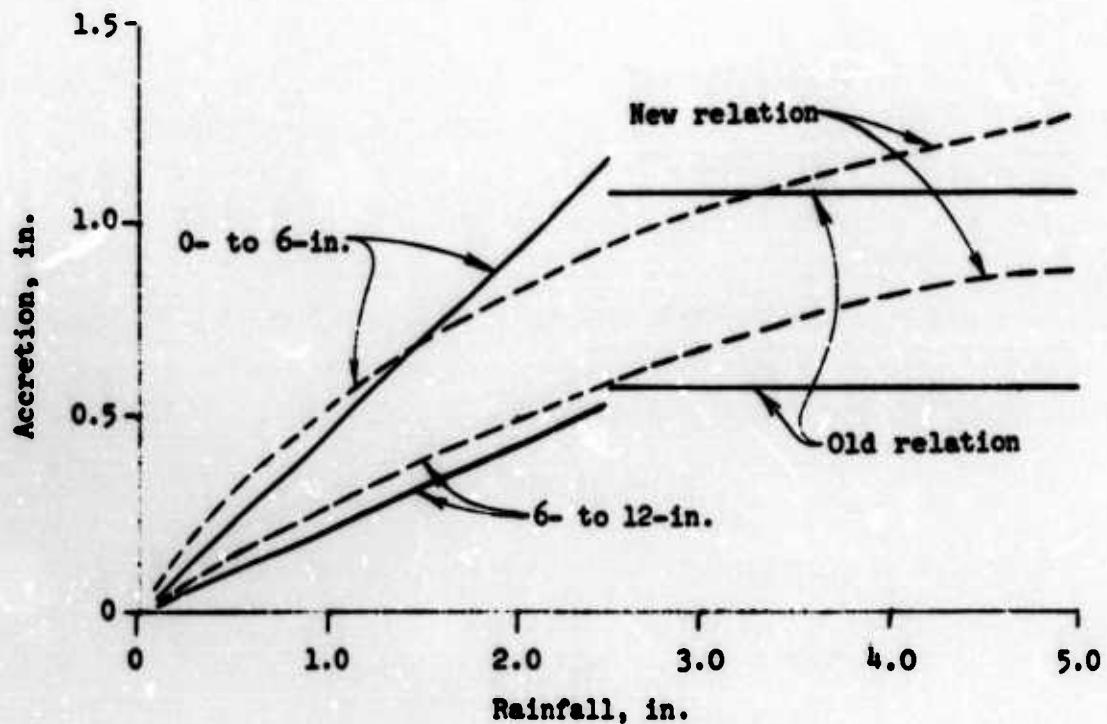
	Soil Layer	
	0- to 6-in.	6- to 12-in.
Soil moisture range	1.50	1.00
Available storage prior to rainstorm	1.50	1.00

Fig. 6. Old and new accretion relations

Depletion relations

15. Depletion (moisture loss) is due to evaporation, transpiration, and drainage. The rate of depletion is controlled primarily by the effect of weather (ambient temperature, day length, humidity, wind velocity, etc.) on evaporation and transpiration and the amount of moisture above field

minimum moisture content. Three seasons are employed in the prediction: summer, transition, and winter. The amount of moisture in the soil at any given time is related to the textural properties of the soil. Therefore, to make a prediction it is necessary to measure or estimate the textural properties of the soil and to know the season of the year.

16. The most accurate depletion relations are the specific relations for a site. These are derived from interrain portions of a daily graph of measured soil moisture contents for a given soil layer and season. Typical depletion relations are shown in fig. 7. On the left of this figure the derivation of a single depletion curve from a family of eight actual depletion curves is shown for the summer season. The deviation of each of the individual curves from the derived curve indicates that some error in prediction will likely occur when the derived curve is used for prediction at this site. The curves shown on the right in fig. 7 are the derived curves for each season. The greatest source of error involved in using these curves for predictions occurs with a change in season, which results in an abrupt change in depletion. Relative depletion rates by seasons for a typical prediction are shown in fig. 8. Note that the predicted rate is constant for a season and that the change is abrupt with a change in seasons. The curved line on this figure, which was drawn to average the abrupt changes with seasons, probably is closer to the actual depletion rate. It is also highly probable that day-to-day variations in weather would result in changes of small magnitude above and below this averaged curve.

17. The prediction system does not employ an established procedure for the determination of the day when seasonal changes in depletion should be made. This determination is left to the judgment of the user based on climatic and vegetational changes and reference to a table listing some observed transition dates at several locations in the U. S. A few years ago a tentative method was developed for selection of the day for each seasonal change based on climate, soil, topographic position, and vegetation. It is believed that use of this method would result in more accurate moisture predictions.

18. The moisture prediction system could also be improved by
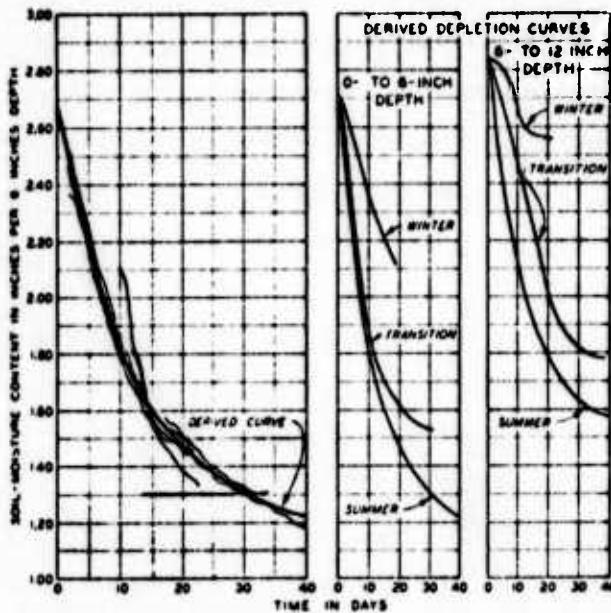
Fig. 7. Specific depletion curves

Month and season of depletion
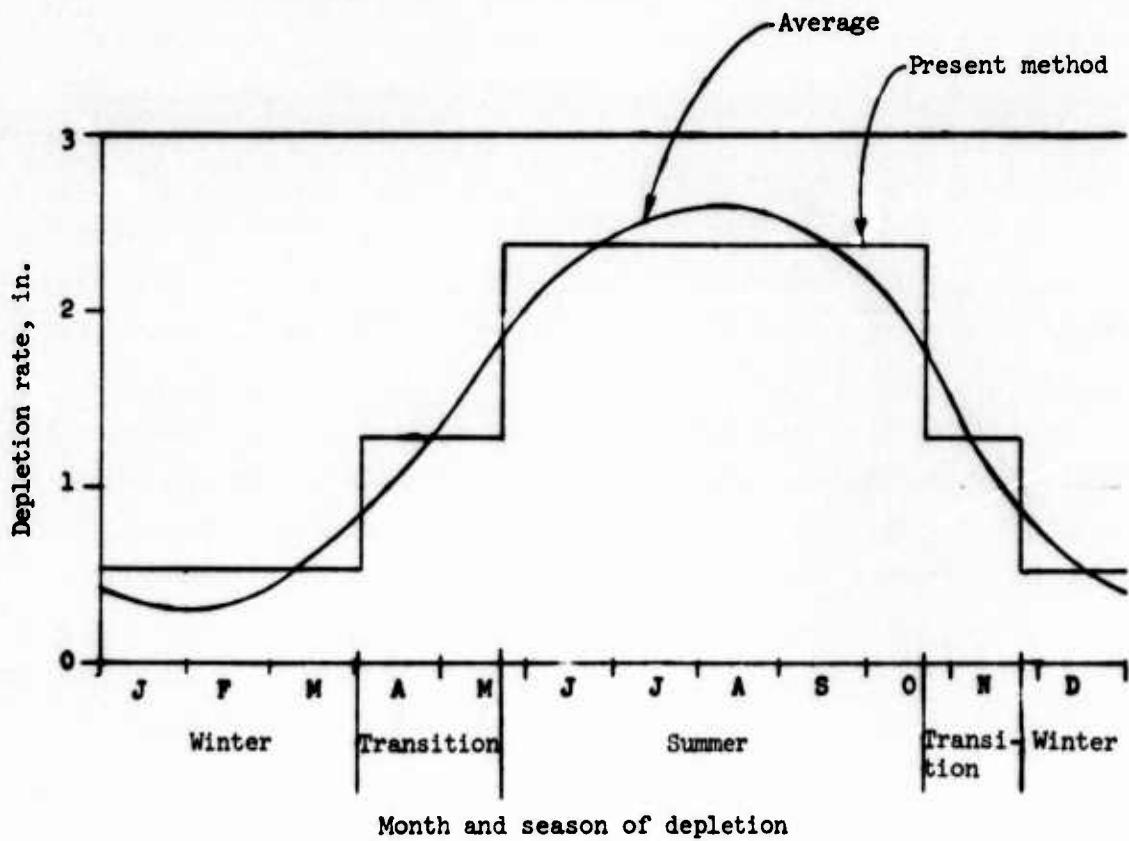
Fig. 8. Relative depletion rates

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considering other environmental factors in the determination of a seasonal depletion rate. Weather factors that might be considered include temperature, humidity, wind velocity, rainfall less than minimum size storm, and length of day. Vegetation factors that might be considered include species, density, stage of growth, and physical characteristics of the plants. Soil factors that might be considered include available soil moisture above field minimum, soil moisture range between field maximum and field minimum, and topographic position.

19. Average depletion relations for the temperate zones of the U. S. have been derived from the 0- to 6-in. and the 6- to 12-in. soil layer for sand, silt, and clay. Sets of relations were developed for each season (winter, summer, and transition). These relations, with adjustment of summer curves for measured or estimated ranges between field maximum and field minimum moisture content, are used in the prediction method when specific depletion relations are not available. The average depletion curves are shown in fig. 9. The accuracy of the curves was checked by comparing the values from the average curve with the values from each of the specific curves used in the development of the average curve. The mean absolute deviations of the average curve from the specific curve after 10 days of depletion from field maximum moisture content for the 6- to 12-in. soil layer for the summer, winter, and transition seasons were 0.24, 0.10, and 0.15 in., respectively. If the average curve had been compared with sites other than those used in its development the deviation would have been greater.

20. Using field minimum moisture content as a common origin, average summer and winter curves from fig. 9 were superimposed over each other (fig. 10). A comparison of these curves shows a remarkably small deviation between them and between an average curve derived from the individual curves. This indicates that the primary factor influencing soil moisture depletion is the amount of moisture above a seasonal field minimum moisture content. The average curve may be defined by the following equation:

$$M_2 = M_1 e^{-kt}$$
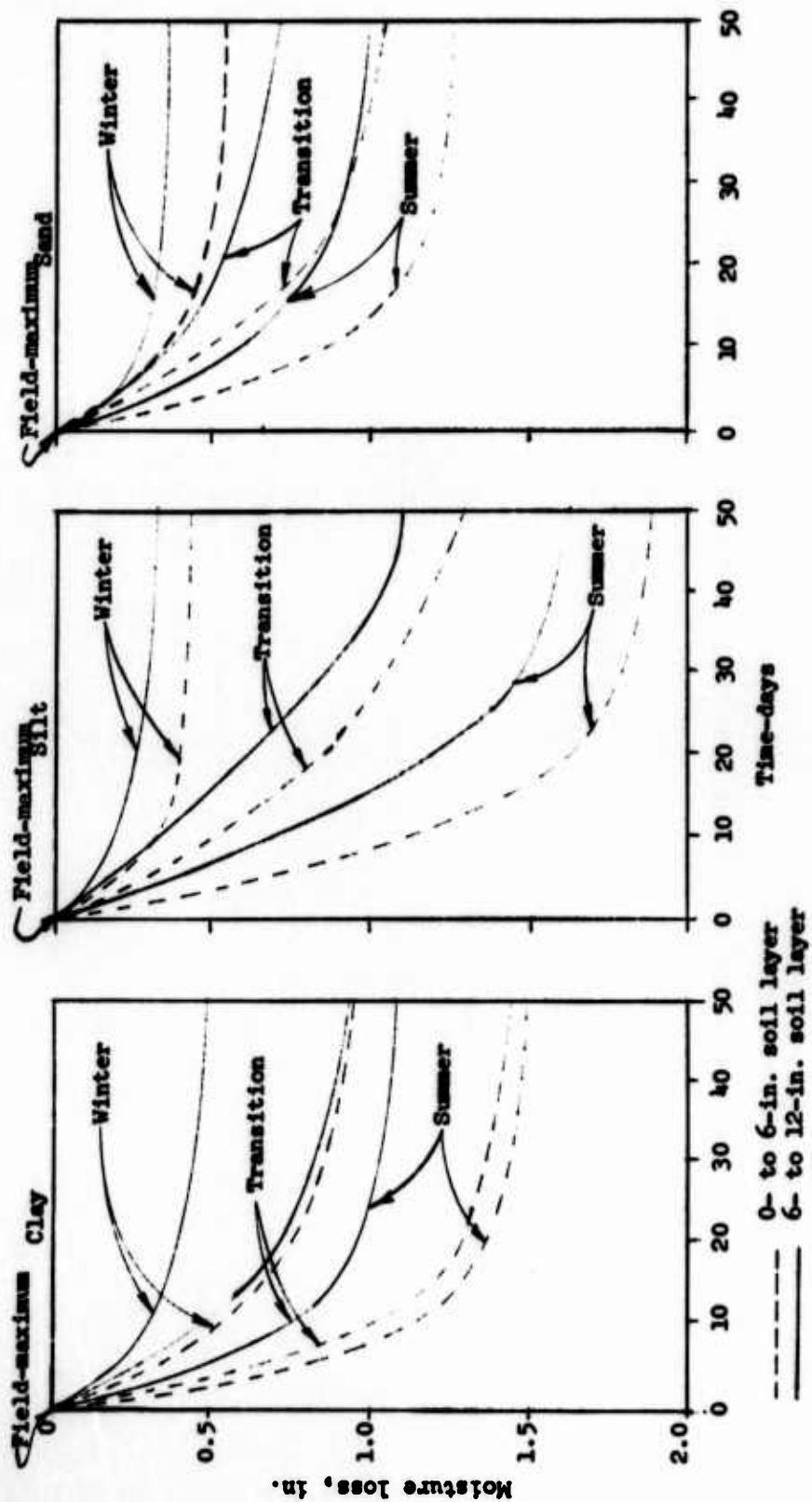
Fig. 9. U. S. average moisture depletion rates
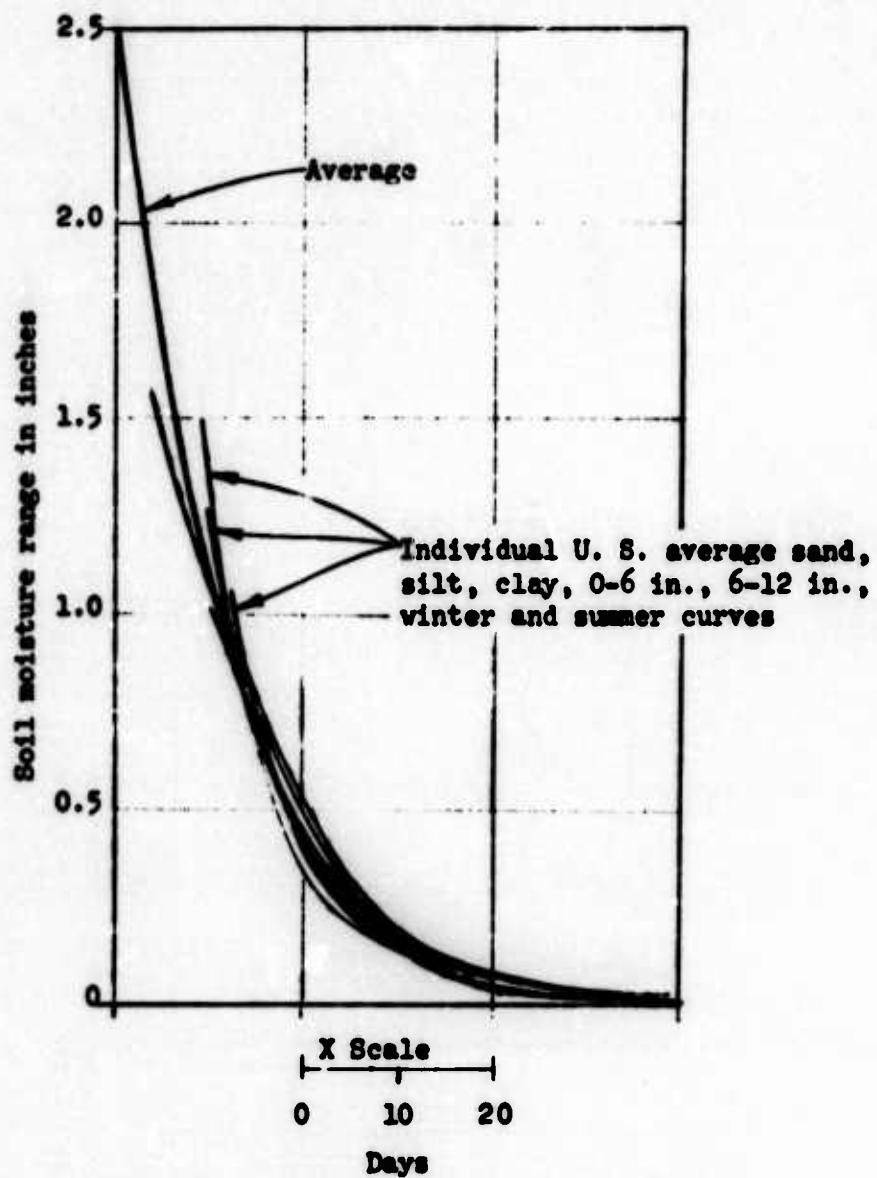
Fig. 10. Comparison of depletion curves

where:

  M_2 = final moisture content above field minimum

  M_1 = initial moisture content above field minimum

  e = 2.718

  k = depletion coefficient (0.09 for U. S. average curve)

  t = time between rainstorms in days

For one day of depletion, the equation simplifies to:

$$\Delta M = M_1 - M_2 = 9 \text{ percent } M_1$$

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21. In the equation, the depletion coefficient k may be held constant for the entire year, in which case the field minimum values would change with the season; or the coefficient k may vary with seasonal or daily changes in weather, in which case the field minimum values would always be constant. Use of the latter method would be more advantageous because it can easily be programmed for the computer analysis. A computer program is now being prepared to check the method in zones where changes in climate during the year have an appreciable influence upon depletion. The method has already been checked in the tropics where seasonal changes do not have an appreciable influence on rate of depletion and has been found to provide more accurate moisture predictions than the present method (using average seasonal curves).

22. It is proposed, therefore, that the new equation with a variable coefficient be developed and used in lieu of the existing depletion method.

Other Deficiencies

23. Deficiencies of the moisture prediction method that are common to all prediction factors or have a nonfactor-connected influence on prediction accuracy are discussed in this section of the paper.

Other factors

24. Probably the greatest deficiency of the prediction method is that not all of the factors influencing soil moisture balance are considered. For example, such factors as surface air flow, vegetation species and structure, heat flux, and others are not considered.

Time period

25. Means are not available for predicting the soil moisture content at a particular time of the day. The selection of a 24-hr time period between predictions imposes a serious limitation on the utility of the method. The 24-hr prediction period also does not permit consideration of rainfall intensity on accretion, and does not allow for accretion and depletion on a day with a short period of rain followed by a long period of sunshine.

Accuracy and range of basic data

26. The development of a more accurate prediction method has been limited by the questionable accuracy of some of the basic data and by the limited number of environmental factors used in the development of the prediction relations. At most of the data collection sites the number of samples taken was insufficient to determine the true statistical mean of each factor.

Natural soil variation

27. One possible deterrent to increasing the accuracy of the predictions is the amount of natural variation within a soil. This subject has been discussed in another paper.* However, it is worthy of mention here that this variation might be as high as 25 percent of the average value of a soil factor within an area the size of a vehicle.

Interaction of prediction factors

28. As the final predicted moisture content is the net result of the summation of the effect of each of the factors entering into a prediction, the interaction of these factors exerts an important influence on the accuracy of the prediction. For example, a certain erroneous factor might cause the predicted moisture content to be increased, whereas error in another factor might cause it to be decreased, each factor thereby offsetting the other's error. Thus, the errors involved in any one factor are often reduced in effect. However, the opposite sometimes occurs.

New Method

29. This investigation has shown how each of the prediction factors influences the accuracy of a prediction and has revealed some serious deficiencies in the present method of prediction. Some suggestions have been given for improving accuracy of prediction. The improvements may be incorporated into the method. However, in view of the deficiencies of the present factors and prediction method, and the possibility that no amount

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* Appendix E of this report entitled "Influence of Soil Variability on Soil Moisture and Soil Strength Predictions," by H. D. Molthan.

of work within the confining limitations of the method will improve it to the accuracy needed for practical application in trafficability prediction, it is suggested that a new method be developed. The procedures of the present method have merit and should be used to guide this development. An appreciable amount of information on factors known or suspected to have an influence on the soil-water balance should be collected over a wide range of environmental conditions at various intervals and times. New data-collection methods and equipment should be devised for use in developing and testing this new method. The relations of factors to moisture content should be tested in the laboratory and the field. The amount of natural variation of moisture that can be expected to occur from point to point in a soil should be measured and characterized so that it may be used as a guide in the development of the method. The method should be as simple as possible and yet capable of predicting moisture content as accurately as required for all pertinent military activities.

APPENDIX C: A TENTATIVE SOIL STRENGTH PREDICTION SYSTEM

by

J. G. Collins

CONTENTS

APPENDIX C: A TENTATIVE SOIL STRENGTH PREDICTION SYSTEM

PART I: INTRODUCTION

Background

1. The Waterways Experiment Station was requested by the Engineer Board in 1945 to assist in developing procedures for measuring soil trafficability in order that the off-road performance of military vehicles could be predicted. In response to this and succeeding requests, several test programs designed to establish soil-vehicle performance relations were conducted. Some of the results of tests on soils with fines (for purposes of this paper, soils with fines include both fine-grained soils and sands with fines, poorly drained) are discussed in the following subparagraphs.

a. A trafficable soil condition was defined as one which permits 40-50 passes, with stopping if necessary, of a given vehicle operating at slow speeds in the same ruts. This condition also allows the vehicle to enter the area, stop, back out of the ruts while turning, and retreat from the area.

b. The 6- to 12-in.* soil layer was found to be the critical layer in that its strength is a primary factor governing the performance of most military vehicles, performance being evaluated on the basis of a vehicle's capability of completing 40-50 passes.

c. For prepared soils, consistent relations were found to exist between the cone index of the critical layer and vehicle performance.

d. For natural soils, it was found that soil strength may change with traffic due to remolding, and that the remolded strength (rating cone index) of the critical layer is the primary factor governing vehicle performance.

e. For every vehicle tested, a characteristic minimum rating cone index (vehicle cone index) was found to exist below which the vehicle could not complete 40-50 passes. Vehicle cone index is dependent upon, and can be estimated from, vehicle parameters but is independent of soil factors. A condensed tabulation of vehicle cone indexes of standard military vehicles is given below.

Vehicle Cone Index Range	Vehicles
20-29	The M29 weasel, M76 otter, and Canadian snowmobile are the only known standard vehicles in this category
30-49	Engineer and hi-speed tractors with comparatively wide tracks and low contact pressures
50-59	Tractors with average contact pressures, tanks with comparatively low contact pressures, and some trailed vehicles with very low contact pressures
60-69	Most medium tanks, tractors with high contact pressures, and all-wheel-drive trucks and trailed vehicles with low contact pressures
70-79	Most all-wheel-drive trucks, a great number of trailed vehicles, and heavy tanks
80-99	A great number of all-wheel-drive and rear-wheel-drive trucks, and trailed vehicles intended primarily for highway use
100 or greater	Rear-wheel-drive vehicles and others that generally are not expected to operate off roads, especially in wet soils

In short, therefore, the original request of the Engineer Board was satisfied, i.e., a procedure for measuring the trafficability of soils was developed.

2. Recently, investigations have been made into the one-pass performance of vehicles on fine-grained soils. Results are not conclusive. In accordance with the 40-50 pass criteria, however, the results indicate that the capability of a vehicle for completing one pass on a given soil, providing adequate traction capacity exists, is dependent upon the cone index of the soil corrected for remolding effects. The results indicate that the critical layer concept may have to be modified somewhat for one-pass performance.

3. At the request of the Corps of Engineers, a study was initiated in 1951 by the Forest Service, USDA, to develop a method for predicting the moisture content of the 6- to 12-in. soil layer. Specifications were that the method be simple enough to permit its use by nontechnical personnel and that it be based on data readily available or easily obtainable in the

field. A method was developed in the following years and was reported in 1954.*

4. Coincident with the development of a moisture prediction system, attempts were being made to establish relations between soil strength and other soil and site factors. It was felt that such relations could be used in conjunction with the moisture prediction system to forecast soil trafficability. Significant progress has been made in this study.

Purpose

5. The purpose of this paper is to present those relations which have been established between rating cone index and soil and site factors and to show how these relations can be used to predict soil trafficability strength.

Scope

6. As indicated in previous paragraphs, the WES procedures require some measure of the remolded soil strength of an area if an estimation of a vehicle's performance in terms of passes completed on that area is to be made. In the study from which the data in this paper were obtained, two methods for predicting rating cone index were presented. One used both cone index and remolding index relations with soil and site factors, while the other used rating cone index relations with soil and site factors. Only information pertaining to the latter method is included herein.

7. When the original study was initiated, data from 116 test sites were available. However, data from only 38 sites were used in developing a system for predicting rating cone index. Data from the remaining sites were not used for one or more of the following reasons: (a) less than five rating cone index-moisture content (RCI-MC) values were available for analysis, (b) the range of RCI values was too small, and (c) the RCI-MC

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* U. S. Army Engineer Waterways Experiment Station, CE, Forecasting Trafficability of Soils; The Development of Methods for Predicting Soil Moisture Content. Technical Memorandum No. 3-331, Report 3, vols 1-3 and appendix, Vicksburg, Miss., October 1954.

relation was not statistically significant at the 0.05 level.

8. Of the 38 sites noted above, 13 were in the southeastern sector of the Continental United States (CONUS), 17 in the remaining sectors of CONUS, 3 in Alaska, 3 in Puerto Rico, and 2 in Panama. A total of 5 to 53 sampling visits were made to each site. Differences existed in site areas and sampling intensities for soil strength and soil moisture content, as illustrated below.

No. of Sites	Site Area sq ft	Number of Observations per Visit		
		Moisture Content, %	Cone Index	Remolding Index
25	72	4	6	4
5	440	5	20	5
5	784	4	6	4
1	1600	1	3	1
2	1600	4	12	4

Differences such as those shown above are important. Although generally not considered in the analysis in terms of their effects on the variance of strength, they should be recognized in the interpretation of results.

9. All relations herein were derived on the basis of data taken from the 6- to 12-in. layer and, therefore, apply only to that layer.

10. Linear regression techniques were used extensively in the analysis. Because transformations of the dependent variables were sometimes made, relations were evaluated in terms of deviations of the untransformed dependent variables as well as in terms of statistical measures. Multiple factor relations were used to predict rating cone index at sites for which data existed at the time the original study was made but which could not be used in the derivation of the relations. These relations were also evaluated in terms of predicted rating cone index deviations.

PART II: DEVELOPMENT OF THE SYSTEM

Rating Cone Index-Soil Moisture Content Relations

11. For inorganic soils with fines rating cone index (RCI) decreases
as soil moisture content (MC) increases. A standard, mathematical equation
which adequately defines this trend by sites is desirable if differences
in trends between sites are to be quantitatively related to soil and site
factors.

12. Field data are usually scattered to the extent that the curve
best defining the RCI-MC trend is not always apparent. However, the trend
between cone index (CI) and soil moisture content in laboratory studies on
processed soils can generally be well defined by a logarithmic equation of
the form

$$\log_{10} CI = a - b \log_{10} MC$$

Although the remolding test probably does not duplicate the laboratory
processing of soils, which involves the removal of stones and roots,
thorough mixing, etc., it can be assumed that the two processes are
analogous.

Derivation of rating cone index-soil moisture content relations

13. The logarithmic equation in paragraph 12 was fitted to the
RCI-MC data on a site basis; simple linear regression (least squares)
techniques were used to compute the equations. Of the 80 sites for which
three or more RCI-MC data points were available, 42 of the relations were
significant at or above the 0.05 level.

14. In a simple linear regression analysis the sum of the squares
of the deviations of the dependent variable from the computed line is
minimized. However, the method favors the mean in that high values are
estimated low, and low values are estimated high; this proved to be true
for the derived RCI-MC relations. Hence, new relations were computed

using the reduced major axis procedure for determining slope (b) values, i.e., $b = \sqrt{b_{y \cdot x} / b_{x \cdot y}}$. Results indicated that these relations fitted the data well.

15. Of the 42 sites for which RCI-MC relations were significant at or above the 0.05 level, only 38 were selected for further use. The other four sites were not used because less than five RCI-MC values were available for analysis and/or the range of RCI values was too small. If one assumes that the prediction relations derived from data taken at these 38 sites are generally applicable, one must also assume that similar relations exist for the sites not used in the derivations.

Rating cone index
measurement accuracy

16. Certain levels of RCI are of far greater importance than others in regard to their effect on vehicle performance. Since most military vehicles can operate on soils having RCI's of 120 or greater, the greatest concern is with accuracies of measuring and predicting RCI below this level.

17. The following tabulation shows deviations of measured rating cone index (MRCI) from specific rating cone index (SRCI) (RCI-MC curve values) by progressive increments of SRCI; 381 observations were included in the analysis.

SRCI Increments	No. of Data Points	Average Algebraic Deviation	Average Absolute Deviation	Standard Deviation
10-19	5	+4	5	7
20-29	12	+3	6	11
30-39	28	+4	10	13
40-49	45	+7	11	15
50-59	50	+8	13	18
60-69	40	+8	13	23
70-79	52	+1	16	21
80-89	26	+12	29	47
90-99	60	+2	16	25
100-109	44	+5	24	31
110-119	19	-3	24	29
Total	381			
Arithmetic weighted average		+5	16	23

C6

The data indicate that the logarithmic, reduced major axis relations fit the RCI-MC data well. Although there are small algebraic deviations resulting from the transformation of CI to $\log_{10}$ CI , they show no trend throughout the range of data.

18. The average absolute and standard deviations for the complete range of data are approximately 16 and 23 units, respectively. The deviations generally increase with an increase in the SRCI level.

19. With the analysis used it was automatically assumed that no errors existed in the measured soil moisture content (MMC) values. This, undoubtedly, was not the case. Regardless, however, of what errors are involved, the deviations noted in the above paragraph show how accurately MRCI depicts SRCI (see paragraphs 8 and 15).

Rating Cone Index-Soil Moisture Content
Equation Constants

20. The computed RCI-MC curves produce straight lines if plotted on logarithmic graph paper. The equation for a straight line can be computed if the coordinates of two points on the line, or if the coordinates of one point on the line and the slope of the line are known. Likewise, if an accurate estimate of any two of the above noted constants can be made, the results will be an accurate estimate of the line.

21. From fig. 1 an important fact is indicated; curves showing the RCI-MC relations shift to higher MC values as soil moisture holding capacity (as indicated by field maximum moisture content) increases. This suggests that the position of the RCI-MC curves with respect to the MC ordinate should be related to other soil properties.

22. To test this hypothesis, moisture contents at the 100 and 200 RCI levels were computed from the RCI-MC equations, and attempts were made to establish relations between these equation constants and other soil and site factors. Although the use of MC values at lower levels of RCI would have been preferable, they could not be computed without gross extrapolation in many cases.

Fig. 1. Rating cone index-soil moisture content relations.

F. Max denotes field maximum moisture content (% dry wt)

Soil moisture content (% dry wt)

Rating cone index

Site 181
F. Max = 42.0

Site 58
F. Max = 34.2

Site 28
F. Max = 26.7

Site 85
F. Max = 22.0

Measured values

c8
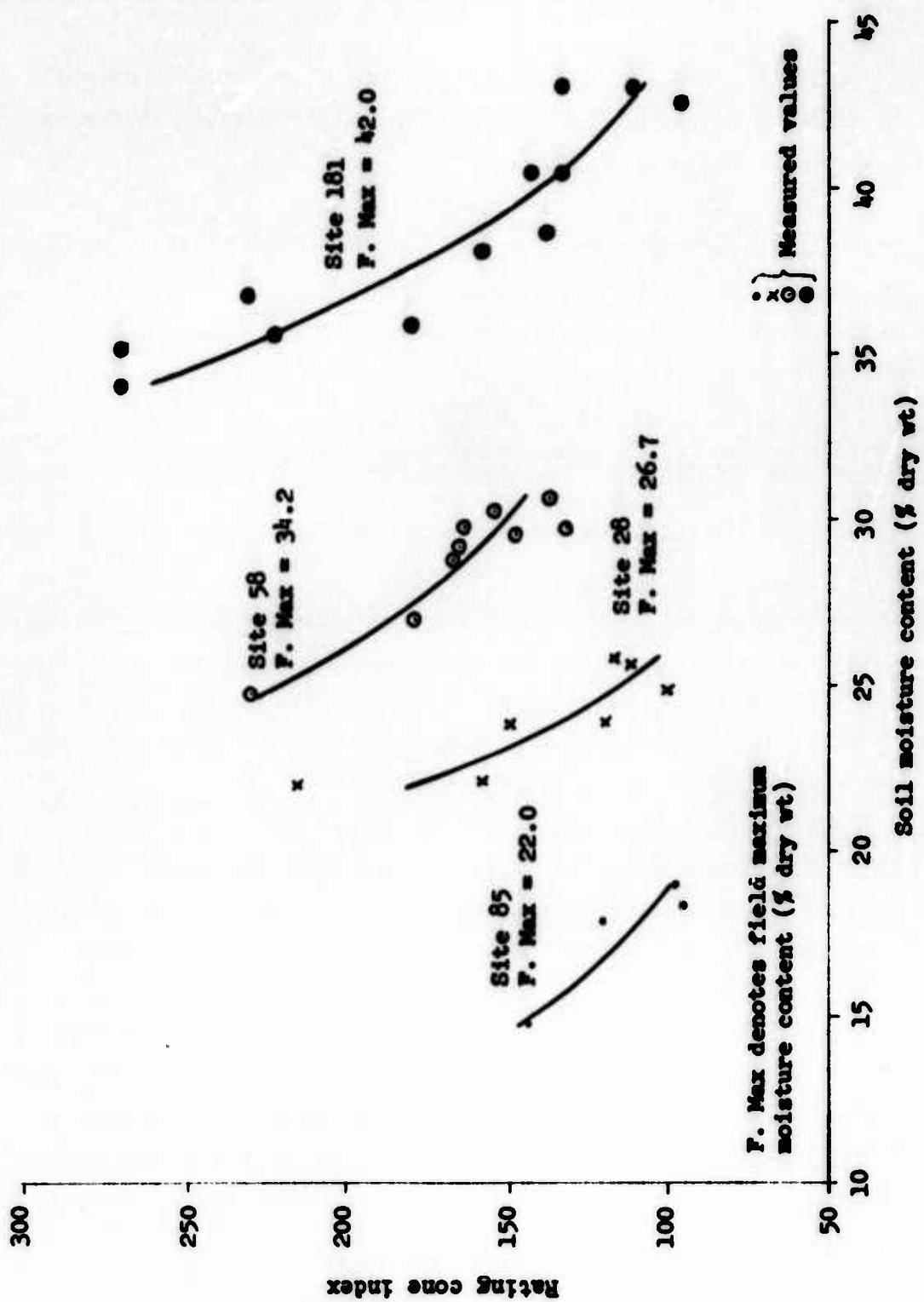
Relation of Constants to Soil
and Site Factors

23. Three ways of relating RCI-MC equation constants to soil and site factors were explored: (a) by soil classes defined in terms of existing soil classification systems, (b) by individual soil and site factors, and (c) by multiple groupings of soil and site factors. Relations were evaluated on the basis of deviations of the RCI-MC equation constants and by other statistical measures.

Soil classes

24. The effectiveness of mean class values for estimating RCI-MC equation constants (i.e., MC at 100 RCI and MC at 200 RCI) was determined on the basis of the Unified Soil Classification System (USCS) and the USDA Textural Classification System. The RCI-MC equation constants were compiled by classes, and the means and average absolute and standard deviations from the means were computed.

25. Data for soil classes of the USCS arranged in decreasing order of plasticity are as follows:

Unified Soil Classification System

Soil Class	No. Sites	MC at 100 RCI			MC at 200 RCI		
		Mean Value	Deviations Avg Abs	Std	Mean Value	Deviations Avg Abs	Std
CH	7	36.0	7.0	8.4	27.9	6.3	7.5
MH	3	47.0	3.0	4.1	37.6	1.6	2.2
CL	14	25.5	2.7	3.9	21.6	2.6	3.6
ML	9	30.2	2.3	3.1	26.3	3.3	4.0
CL-ML	5	22.6	1.1	1.6	19.2	1.8	2.4
All classes	38	--	3.2	4.7	--	3.3	4.5

Only five classes were represented, all of fine-grained materials. There was considerable overlap between some classes; however, the system does serve to indicate that differences of RCI-MC equation constants exist between high plasticity and low plasticity soils.

26. Data for soil classes of the USDA Textural Classification

System arranged in an increasing order of grain size are as follows:

USDA Textural Classification System

| Soil Class | No. Sites | MC at 100 RCI | | | MC at 200 RCI | | |
| | | Mean Value | Deviations | | Mean Value | Deviations | |
			Avg Abs	Std		Avg Abs	Std
C	4	44.2	4.7	6.8	35.2	4.4	6.0
SiC	2	44.2	1.7	2.4	33.7	2.3	3.2
SiCL	2	29.9	0.8	1.1	21.1	1.9	2.7
CL	1	24.1	--	--	20.9	--	--
SiL	26	26.9	3.6	5.1	23.2	3.1	4.7
L	3	28.2	5.9	7.7	23.4	5.0	7.0
All classes	38	--	3.7	5.4	--	3.3	5.0

Only six of twelve classes were included in the analysis, and sandy soils were not represented. Also the numbers of observations per class were low except for the silt loam class. Mean class values appear to be divided into two groups, clay and silty clay soils having much higher RCI-MC equation constants than the other four soil classes represented. Deviations were larger than those of the USCS.

Individual soil and site factors

27. Soil and site factors commonly used in soil strength and soil moisture investigations were studied individually to determine if they were related to the RCI-MC equation constants. The following twelve factors were used: fines content; liquid and plastic limits; plasticity index; organic matter, sand, silt, and clay contents; dry density; moisture content at 0.06- and 15-atm tension; and wetness index.* Linear regression analyses were used in attempts to establish relations. A summary of the results is presented in table C1, and highly significant regressions are shown in fig. 2.

28. Caution should be exercised in the interpretation of relations. The relations have not been shown to be of a cause-and-effect nature. Also,

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* Wetness index is an expression of the degree of wetting which takes place at a site. It is determined on the basis of water table depth or, for sites with no water table, the depth of penetration of water from precipitation.
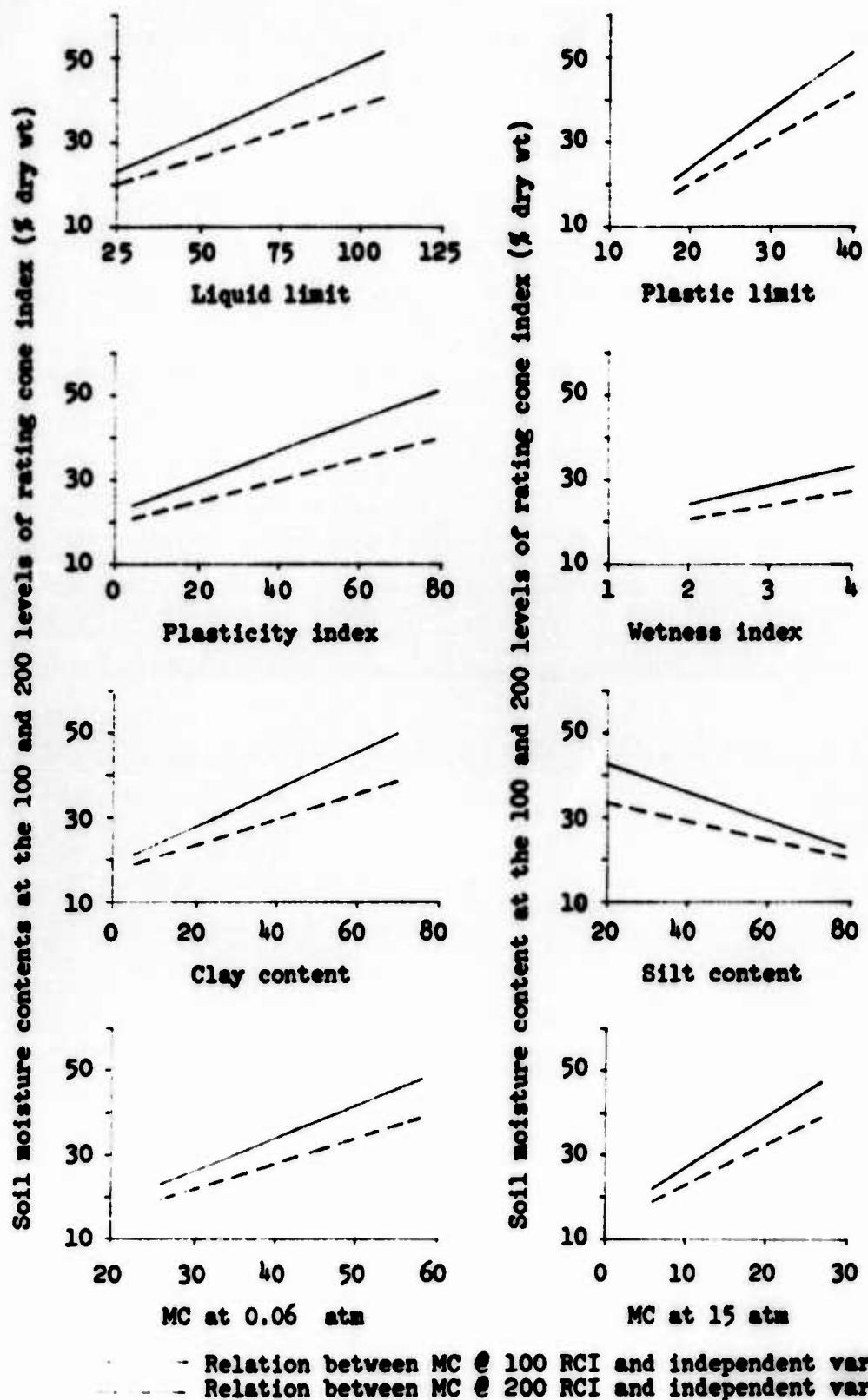
Fig. 2. Soil moisture contents at the 100 and 200 levels of rating cone index as they relate to some soil and site factors.

an analysis of clay type was not made for any of the soils, and clay type is known to be a factor which influences soil strength.

29. The RCI-MC equation constants had highly significant (0.01 level) relations with eight of the twelve soil and site factors. The four exceptions were with dry density, and fines, organic matter, and sand contents. Because of the limited ranges included in the analysis of the latter three factors, results shown in regard to their relations with the RCI-MC equations should not be considered as conclusive.

30. Evenly distributed dry density values over a somewhat normal range were included in the analysis. Results indicated that little of the variation in the RCI-MC equation constants was associated with the undisturbed dry density of soil. This is not surprising; laboratory tests on processed soils show that CI differences at a given MC are far greater between low, medium, and high plasticity soils than they are for any one of the three soils compacted to various dry densities. This may be due to the fact that the same amount of lubricant (water) per unit mass of soil exists at a given MC regardless of dry density. It should also be noted, however, that RCI is a strength measure of a remolded soil, the density of which may differ greatly from the undisturbed dry density of the same soil.

31. Relations between wetness index and the eleven soil properties included in the analysis were very poor. It is therefore difficult to understand why relations existed between the RCI-MC equation constants and wetness index, unless it is an indicator of soil structural changes which may occur under varying degrees of wetness.

32. The accuracies of estimations of RCI-MC equation constants through the use of either liquid limit or plastic limit are comparable to those arrived at through the use of the USCS. Since these two soil properties are used either directly or indirectly in delineating the classes of the USCS, it would seem that the established criteria of the USCS for grouping soils have little significance insofar as the estimation of RCI-MC equation constants is concerned.

33. Of the eight pairs of highly significant relations, seven had positive regression coefficients (slopes), and one, the pair of relations with silt content, had negative coefficients. The signs of the regression

coefficients indicate that at a given RCI level (for fine-grained soils) MC increases are associated with increases in plasticity and decreases in grain size.

34. Conversely, the data indicate that at a given MC, RCI increases are associated with increases in plasticity and decreases in grain size. For example, at an MC of 35 percent, RCI increases from 100 to 200 as plastic limit increases from 28 percent to 34 percent (see fig. 2).

35. Fig. 2 shows that for any given soil or site factor, the relation to MC at 200 RCI has a flatter slope than the relation to MC at 100 RCI. From this and the position of the two regression lines with respect to each other, it can be concluded that each of the factors is related to the slope of the RCI-MC relations, at least between the 100- and 200-RCI levels. The slopes of RCI-MC relations become flatter with increases in plasticity and decreases in grain size. As an example, for soils having a clay content of 20 percent, an average MC loss of 4.5 percent is required to increase RCI from 100 to 200; for an equivalent strength gain for soils having a clay content of 60 percent, an average MC loss of 9.7 percent is required.

Multiple soil and site factors

36. Multiple linear regression analyses were made between the RCI-MC equation constants and five soil and site factors. The soil and site factors (independent variables) selected were fines content (F), liquid limit (LL), plasticity index (PI), clay content (C), and wetness index (WI). The derived relations are shown below.

MC at 100 RCI = -4.0 + 0.049F + 0.883LL - 0.817PI + 0.224C + 0.48WI

MC at 200 RCI = -5.0 + 0.071F + 0.712LL - 0.677PI + 0.151C + 0.63WI

37. Both relations were highly significant. Multiple correlation coefficients for the relations with MC at 100 RCI and MC at 200 RCI were 0.949 and 0.900, respectively; average absolute deviations of the estimated RCI-MC equation constants were 2.0 and 2.1 percent, respectively; and standard deviations were 2.5 and 2.8 percent, respectively. Since there was little difference in estimation accuracies at the two levels, good relations with MC at lower RCI levels probably could have been established if data had been available.

38. The accuracies of the various methods for estimating RCI-MC constants in terms of average absolute deviations are:

RCI-MC Equation Constant	Method			
	Classification System		Best Single Factor	Multiple Factor
	USCS	USDA	Relation (LL)	Relation
MC at 100 RCI	3.2	3.7	2.9	2.0
MC at 200 RCI	3.3	3.3	2.8	2.1

The data show that the multiple factor relations resulted in improved estimations of RCI-MC equation constants. The fact that estimation accuracies of the RCI-MC equation constants approach the measurement accuracy of MC (on a four-sample basis) justified using the multiple factor relations to predict RCI.

PART III: PREDICTION OF RATING CONE INDEX

39. As noted in paragraph 20, if the coordinates of two points $(X_1, Y_1, \text{ and } X_2, Y_2)$ on a line are known, the equation for that line can be determined. For the equation $Y = a + bX$, computations are as follows:

$$b = \frac{Y_2 - Y_1}{X_2 - X_1}$$

and

$$a = Y_1 - bX_1$$

Using the relations shown in paragraph 36, and following the computations shown above, RCI-MC relations can be estimated. Furthermore, RCI can be predicted on the basis of MMC values, and the prediction accuracies of RCI can be evaluated on the basis of MRCI values.

40. Predictions of RCI were made for the following groups of sites: prediction-development (PD) sites used in establishing relations; PD sites not used in establishing relations; water table study sites located in Arkansas, Louisiana, and Mississippi; and survey sites (used to check moisture prediction relations) located in the southern, northeastern, lake states, and intermountain regions of CONUS. Evaluations on the basis of algebraic, absolute, and standard deviations were made for the <59, $60-79$, and $80-119$ increments of MRCI. Results of this analysis and the measurement accuracies of RCI discussed in paragraphs 17-19 are presented in table C2.

41. It is obvious that the predictions were not good. Average absolute and standard deviations for all the data were approximately 30 and 40 RCI units, respectively. Prediction accuracies were very low with respect to the range of measured RCI values considered. The fact that low RCI values are generally predicted high and high values are generally predicted low (as shown by plus and minus algebraic deviations) indicates that the system in its present form might be improved to some extent.

42. Some factors which may have contributed to the poor predictions are discussed in Part IV following.

PART IV: LIMITATIONS OF THE SYSTEM

43. That all prediction systems (and, for that matter, classification systems) have limitations is a generally accepted fact. They are usually limited to the original design objectives of the derivations, by the prediction parameters, and by prediction accuracies. The discussion which follows is primarily related to the prediction parameters (soil and site factors) which were incorporated directly or indirectly into the system heretofore presented.

Ranges of Soil and Site Factor Values

44. As a general rule, a relation is valid only within the limiting values of the parameters used in the derivation of the relation. Beyond these limits the relation may change, or in fact, may not even exist. The limiting values of the soil and site factors used in the derivation of RCI prediction relations are summarized below.

Soil or Site Factor	Lowest Value	Highest Value
Fines content	63	100
Liquid limit	25	107
Plasticity index	4	79
Clay content	5	70
Wetness index	2	4

It is obvious that the prediction relations specifically apply only to plastic, fine-grained soils.

45. Perhaps less obvious than that limitation discussed above, but still of importance, is the fact that all the factors which influence the dependent variable may not be included in a prediction relation. If this is the case, the relation is valid only within the limiting values of the nonincluded influencing factors that existed at the time the included factors were being measured. Of course, strict adherence to this limitation would render most prediction systems useless; however, it should at least be followed at a practical level.

46. That the RCI prediction results were poor may in part be

attributed to extrapolations being made beyond the limits of factors which were incorporated either directly or indirectly into the prediction relations.

Accuracies of Soil and Site Factor Values

47. The accuracies with which measurements or estimations are made of soil moisture content and the soil and site factors used in the derivation of the prediction relations will influence RCI predictions. These factors are discussed briefly in the following paragraphs.

Soil moisture content

48. To determine the effect of measurement or estimation accuracies of MC, the following procedure was used. The average changes in MC were computed for eight changes in RCI ($\pm$10, 20, 30, and 40 units) at six levels of SRCI (50, 100, 150, 200, 250, and 300) on the basis of RCI-MC relations for the 38 sites from which the prediction relations were derived. Results are shown in fig. 3.

49. The average MC change for a given RCI change increases as the RCI level decreases. To arrive at an average RCI accuracy of $\pm$20 units, MC at the 50-, 100-, and 150-RCI levels must be determined within approximately 2.5 $\left(\text{i.e. } \dfrac{2.2 + 2.8}{2} \right)$, 1.4, and 0.9 percent, respectively, providing the RCI-MC relation is known. The standard deviation of the mean measured MC of a site on a four-sample basis is approximately 1.5 percent on the average. Using this figure and interpolating, it is apparent that RCI can be determined 68 percent of the time ($\pm$1 standard deviation) within approximately $\pm$12 $\left(\text{i.e. } \dfrac{11 + 13}{2} \right)$, 23, and 33 units at the 50-, 100-, and 150-RCI levels, respectively, if the RCI-MC relation is known.

Soil and site factors

50. The effects of a per unit change in each of the soil and site factors used in the derivation of prediction relations on the estimated RCI-MC equation constants are:
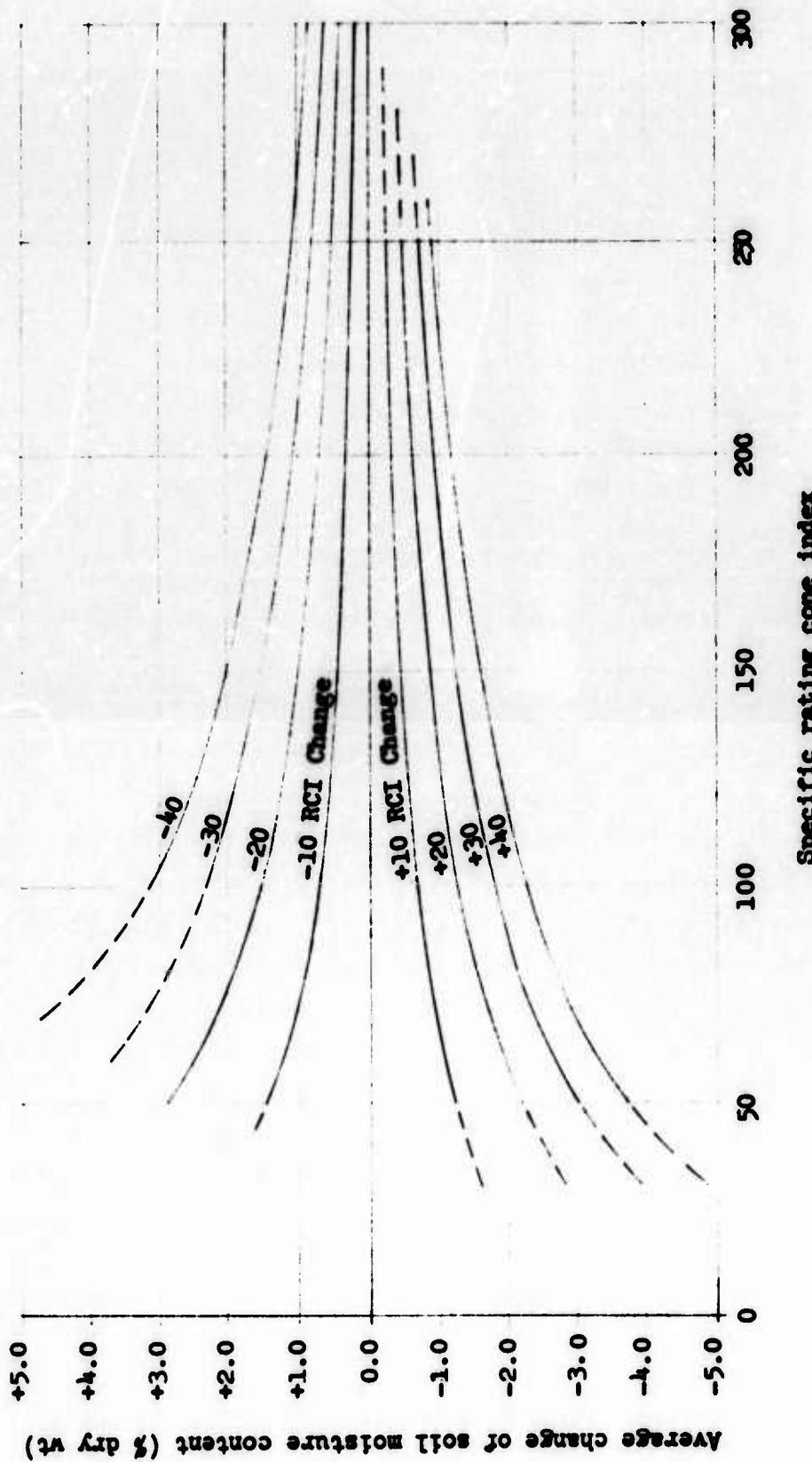
Fig. 3. Average changes in soil moisture content corresponding to given changes in rating cone index (38 sites).

	Change in Estimated Equation Constants (% dry wt) Corresponding to a 1-Unit Change in Soil and Site Factors	
Factor	MC at 100 RCI	MC at 200 RCI
Fines content	0.05	0.07
Liquid limit	0.88	0.71
Plasticity index	0.82	0.68
Clay content	0.22	0.15
Wetness index	0.48	0.63

The data show that a small change in liquid limit or plasticity index will result in a significant change in the estimated RCI-MC equation constants and, as indicated by fig. 3, in predicted RCI.

51. Statistical evaluations of how accurately soil factors used in the prediction relations depict the true mean value of a site are limited. However, recent studies indicate that the standard deviation of mean measured liquid limit and plasticity index values of a site on a two-sample basis are approximately 4 and 3 percent, respectively; when considered in terms of predicted RCI, these variations are large.

52. Although the discussion in previous paragraphs is general, it serves to indicate that RCI is sensitive to very small differences in soil characteristics. Thus, it becomes obvious that the soil moisture prediction system and the soil strength relations must be greatly improved if they are to find meaningful use in tactical military problems.

Table C1

Relations Between Rating Cone Index-Soil Moisture Content

Equation Constants and Soil and Site Factors

Soil Site Factor	Low Value	High Value	No. Obs	MC at 100 RCI			Deviation		MC at 200 RCI			Deviation	
				Corr Coeff	Sign. Level	Equation: MC at 100 RCI =	Avg Abs	Std	Corr Coeff	Sign. Level	Equation: MC at 200 RCI =	Avg Abs	Std
Fines content	63	100	38	+0.084	NS	--	--	--	+0.112	NS	--	--	--
Liquid limits	25	107	38	+0.859	0.01	$14.7 + 0.343 \times$	2.9	4.2	+0.792	0.01	$13.8 + 0.248 \times$	2.8	3.9
Plastic limit	18	40	38	+0.866	0.01	$-3.7 + 1.385 \times$	3.4	4.1	+0.862	0.01	$-1.4 + 1.084 \times$	2.4	3.3
Plasticity index	4	79	38	+0.761	0.01	$22.6 + 0.359 \times$	3.9	5.3	+0.683	0.01	$19.8 + 0.253 \times$	3.5	4.7
Organic matter content	0.45	5.34	34	+0.132	NS	--	--	--	+0.070	NS	--	--	--
Sand content	1	39	38	-0.217	0.20	--	--	--	-0.227	0.20	--	--	--
Silt content	20	79	38	-0.608	0.01	$48.9 - 0.319 \times$	4.8	6.5	-0.527	0.01	$37.8 - 0.217 \times$	4.2	5.5
Clay content	5	70	38	+0.792	0.01	$19.5 + 0.437 \times$	3.8	5.0	+0.713	0.01	$17.5 + 0.309 \times$	3.4	4.5
Dry density	59	101	38	-0.345	0.05	--	--	--	-0.319	0.10	--	--	--
MC at 0.06-atm tension	25.8	58.0	28	+0.707	0.01	$3.3 + 0.772 \times$	4.2	6.0	+0.685	0.01	$4.7 + 0.587 \times$	3.5	4.8
MC at 15-atm tension	5.8	27.2	26	+0.872	0.01	$15.0 + 1.197 \times$	2.8	4.0	+0.831	0.01	$13.5 + 0.940 \times$	2.8	3.8
Wetness index	2	4	38	+0.517	0.01	$15.0 + 4.58 \times$	5.9	6.8	+0.502	0.01	$13.4 + 3.56 \times$	4.7	5.5

Table C2

Measurement and Prediction Accuracies of Rating Cone Index

Number of Observations and Deviations
by Increments of Measured Rating Cone Index

Sites	<60				60-79				80-119			
	No. Obs	Deviations			No. Obs	Deviations			No. Obs	Deviations		
		Avg Alg	Avg Abs	Std		Avg Alg	Avg Abs	Std		Avg Alg	Avg Abs	Std
PD* used in analysis	140	+6	11	15	92	+4	15	22	149	+4	22	32
PD used in analysis	131	+22	29	42	101	+15	28	41	140	+10	31	41
PD not used in analysis	69	+16	24	37	52	+20	39	52	138	-14	44	57
Water table	229	+15	21	28	54	+8	21	28	83	-8	29	36
Southern survey	24	+4	15	22	15	-8	17	24	61	-9	24	30
Northeast survey	17	+3	40	64	23	-3	40	52	61	-34	45	52
Lake states survey	11	+2	26	32	22	-10	26	31	64	-33	44	51
Intermountain survey	24	+5	21	30	15	+2	25	30	22	-12	36	46
All sites**	505	+15	24	34	282	+9	29	39	569	-11	36	45

* Measurement accuracy by increments of specific rating cone index.

** Standard deviations are arithmetic average values.

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APPENDIX D: INFLUENCE OF WATER TABLES ON SOIL MOISTURE
AND SOIL STRENGTH

by

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CONTENTS

APPENDIX D: INFLUENCE OF WATER TABLES ON SOIL MOISTURE
AND SOIL STRENGTH

PART I: INTRODUCTION

1. Water tables near the soil surface have an adverse effect on many
military operations. It is either known or can logically be assumed that
they often result in the impaired mobility of vehicles and foot troops and
make many areas highly unsuitable for troop bivouac or the construction of
trenches, foxholes, tunnels, underground structures, surface buildings,
roads, or airfields.

2. It can be concluded, therefore, that a definite need exists for
the capabilities of delineating areas of high water table and of predicting
water table levels. All approaches toward gaining these capabilities
should be explored.

Background

3. A method for predicting the moisture content of the 6- to 12-in.
soil layer was presented in a joint Forest Service-Waterways Experiment
Station report in 1959.[1] As shown in the report, the average absolute
deviation between predicted and measured moisture contents for all soils
tested (625) was 0.31 in. (inches of water per 6 in. of soil; 0.08 in. ≈ 1.0
percent on a dry weight basis). However, the average absolute deviation
for drained soils was notably smaller than that for sites influenced by
water tables, i.e. 0.27 in. as compared to 0.38 in. One of the recommenda-
tions of the report therefore was that "further studies should be made of
soils wet by water tables to determine what soils and sites are influenced
by water tables, and the time of occurrence and duration of the water table
effect."

Studies

4. Three water table studies have been conducted. For purposes of

this paper they are referred to as the Mississippi-Alabama, Arkansas, and Oregon studies. The primary objectives and brief descriptions of the studies are presented below.

Mississippi-Alabama study

5. The primary objective of this study was "to develop a method or scheme for identifying areas where water tables lie within 4 ft of the surface during the wet season."

6. Sites were located in west and east central Mississippi, and west central Alabama. Soils on which test sites were located varied greatly in physical properties and parent material; vegetation varied from herbaceous to forest. The average annual precipitation for the study area as a whole is approximately 50 in., of which about 30 in. falls in the winter and spring months.

7. A total of 58 sites were established. From two to four sites were located along each of 18 transects which were situated transverse to and on one side of secondary streams. Sites along the transects were usually spaced across a bottomland to the toe of an upland slope and occasionally to an upland upper slope. During periodic visits, the depth to water table was measured at each site, and soil strength, soil moisture content, and cumulative rainfall data were collected at one or two sites along each transect.

Arkansas study

8. The primary objective of this study was "to determine and evaluate site factors that affect significantly the inception, duration, and periodicity of seasonal water tables."

9. Data were collected in southeastern Arkansas near the town of Crossett. Soils on which test sites were established were derived from either coastal plain sediments, loess, or alluvium. Most of the soils were silty in texture; fragipans, the upper surfaces of which were at depths ranging from about 6 to 40 in., existed at many of the sites. Most of the study area was forested. Mean annual precipitation is 54 in., of which approximately one-half falls in the months of December through April.

10. A total of 37 sites were established for this study. Sites were located either individually or along transects positioned on upland

flats or across a range of slope positions. During periodic visits, depth
to the water table was measured at each site, and soil strength, soil
moisture content, and rainfall data were collected at the sites located
individually and at one of the sites along each transect.

Oregon study

11. The primary objective of this study was to establish relations
between soil morphological characteristics and water table regimes.

12. Sites were located in west central Oregon near the town of
Shedd. Soils on which sites were established were derived primarily from
lacustrine silts. Soils were silty in texture although pronounced textural
B horizons (clay pans) existed at some sites. Vegetation at all sites was
herbaceous. Mean annual rainfall is approximately 42 in., of which almost
one-half generally falls during November, December, and January.

13. Three sites were located in each of five soil series; only one
site, however, was established within an individual soil series mapping unit.
At each site rainfall and water table data were collected daily; soil
strength and moisture content data were collected periodically.

Scope

14. The findings of the three studies, as applicable, are included
under separate selected topics. These topics include the effects of water
tables on soil moisture and strength of the 6- to 12-in. layer, environmental
factors associated with water table regimes, and a tentative water table
classification scheme.

Limitations

15. It should be noted that the areas from which water table and
associated data were collected were not selected at random. Also, the
numbers of observations are very small in comparison with the populations.
Therefore, findings may not be applicable except under conditions like or
similar to those under which observations were made.

Definitions

16. The terms high water table, near-surface water table, and surface water table are used herein. For purposes of this paper a high water table is characterized by a free surface at an elevation equal to or greater than the minimum elevation at which appreciable amounts of moisture will move by capillarity into the 6- to 12-in. soil layer. For most soils this minimum elevation is comparable to a water table depth of approximately 3 ft (see paragraphs 28-30). A near-surface water table has a free surface within 12 in. of the soil surface. A surface water table has a free surface at or above the soil surface.

PART II: WATER TABLE EFFECTS

17. A brief discussion of the effects of high water tables on the moisture content and strength of the 6- to 12-in. soil layer is presented in the following paragraphs. Findings and conclusions based on data from the three water table studies are generally not new, but they do tend to confirm findings of past studies.

Soil Moisture Content

18. For practical purposes, the only source of moisture for a soil in which a high water table does not exist is precipitation. However, a soil in which a high water table does exist may be considered as having two available sources of moisture, i.e. precipitation and the water table. This basic difference results in differences in field maximum moisture contents and soil moisture depletions.

Field maximum moisture content

19. Previous WES studies have indicated that the field maximum moisture content increases with a decrease in depth to the water table.[1] This, of course, is due to the successive filling of larger and larger pores with water.

20. It is to be expected that for soils subject to a near-surface water table, field maximums are approximately equivalent to moisture contents at 0-atm tension. Data from the Oregon study indicate that this is essentially correct; the average algebraic and absolute deviations of 0-atm tension values from field maximum moisture contents were -0.05 and 0.10 in., respectively. Because of the capillary potentials involved, the larger pores of soils not subject to high water tables are generally not filled during rains of normal intensity. WES studies have indicated that field maximum moisture contents for these soils are approximately equivalent to 0.06-atm tension;[1] studies by other investigators[2,3,4] tend to verify this conclusion.

21. Of interest is the accuracy with which the field maximum moisture contents of soils subject to high water table conditions can be

predicted. Using the following equation, predictions were made on the basis of data collected at high water table sites in the Mississippi-Alabama and Oregon studies: field maximum = 2.06 - 0.012% sand + 0.008% clay + 0.155 wetness index. Even though a water table factor, i.e. wetness index, is included in the equation, field maximum moisture contents were generally predicted low, as shown in fig. 1.

Soil moisture depletion

22. For soils with high water tables as compared to soils without high water tables, a longer period of time is required to deplete from field maximum to a level of moisture common to both soils. This can be explained as follows.

23. Depletion lag. For a soil subject to a surface water table some finite period of time is required for the water table to drop to a depth of 6 in. This, of course, results in a depletion lag. The depletion lag may range from a few hours to several days in length depending upon the permeability of the soil and topographic features of the site. Lags are probably longest for sites with a relatively impermeable layer at a shallow depth or for sites located in topographic depressions or at elevations approximately equal to the elevations of nearby bodies of water.

24. The length of the depletion lag for Oregon site 240 can be determined from the water table recession-time relations shown in fig. 2. The time required for the water table to drop from the soil surface to a depth of 6 in. was approximately 3 days during the winter months.

25. Added depletion. As noted in paragraph 20, field maximum moisture contents for most soils can be approximated by using either 0- or 0.06-atm tension values. For a soil subject to a high water table some finite period of time is required for the water table to drop to a depth of 36 in. (a water table at a depth of 36 in. would exert approximately 0.06-atm tension on the 6- to 12-in. soil layer), and thus to reach a moisture content equivalent to the field maximum of a similar soil without a high water table.

26. The time required for this added depletion to take place is probably dependent upon the same factors which result in a depletion lag
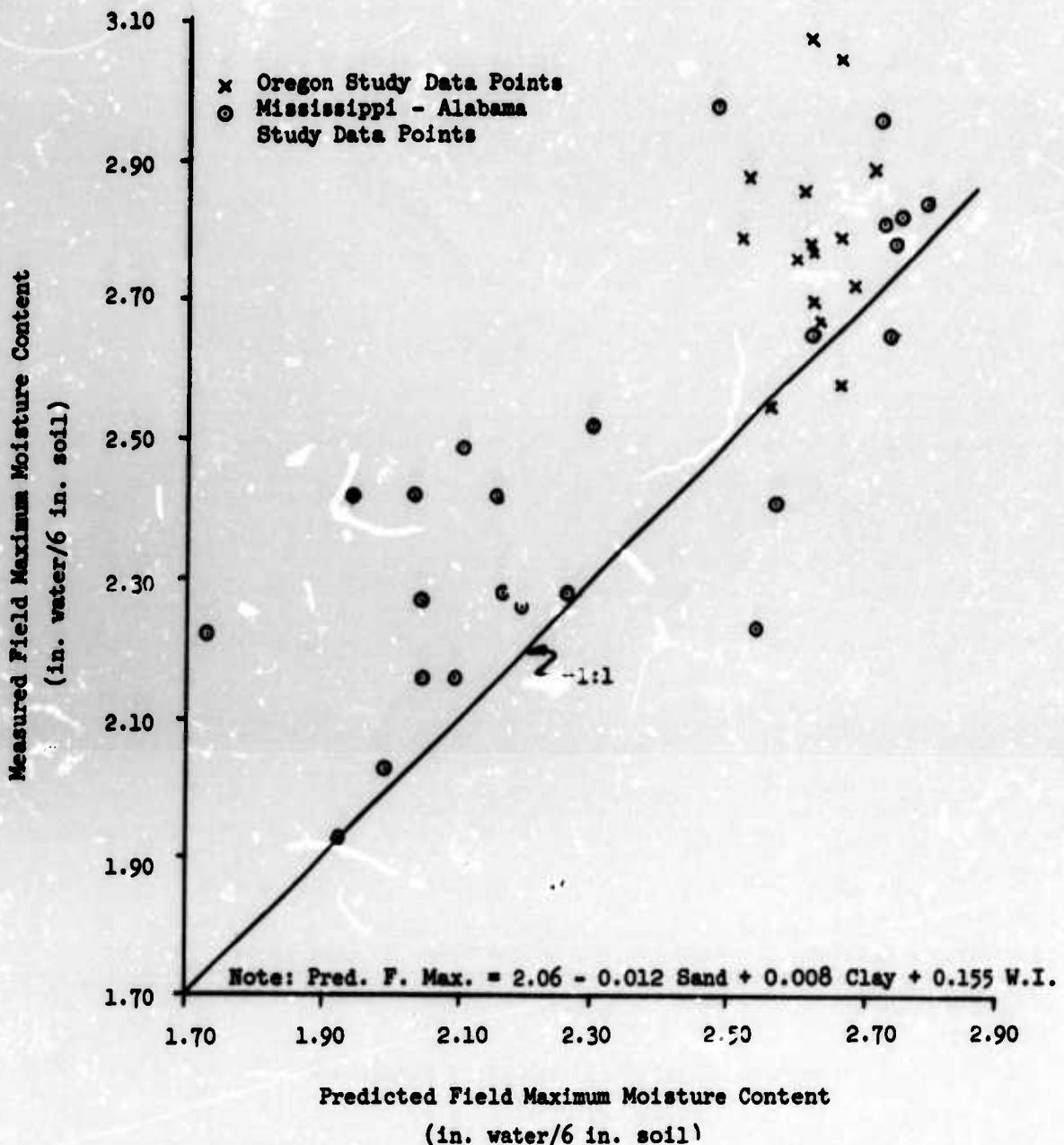
Fig. 1. Measured versus predicted field maximum moisture contents of the 6- to 12-in. soil layer, Mississippi, Alabama, and Oregon studies

D7
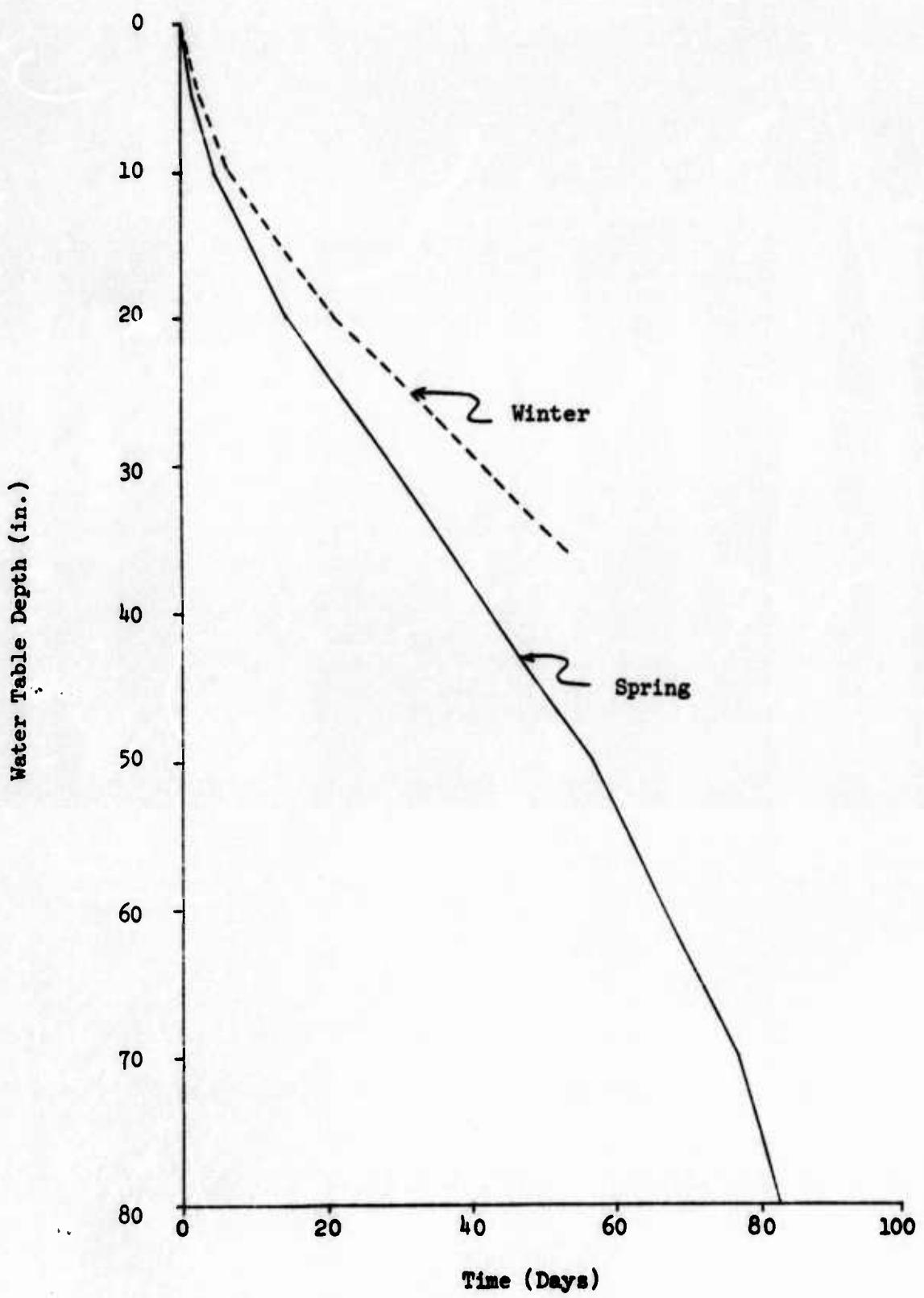
Fig. 2.   Water table recession-time relation; Oregon site 240

(see paragraph 23). For Oregon site 240, the time required for the water table to drop from the 6-in. depth to the 36-in. depth was approximately 52 days during the winter months (see fig. 2).

27. _Capillarity._ If the free surface of a water table lies within a short distance below the 6- to 12-in. soil layer, moisture will be drawn by capillarity from the water table into the 6- to 12-in. layer. This is an accretion mechanism but may more simply be considered as a cause of reduced rates of soil moisture depletion.

28. The maximum depth at which a water table may occur and still act as a supply for appreciable amounts of soil moisture for the 6- to 12-in. soil layer is of importance. This maximum depth has been considered to be 4 ft in past WES studies.[1] This depth corresponds to an effective capillary rise of approximately 90 cm (4 ft - 1 ft ≈ 90 cm).

29. A study by Pierpoint and Farrar[3] showed that the capillary fringe extended approximately 60 cm (24 in.) above either a falling or stationary water table in a medium sand soil. In a study by Keen,[5] it was found that at a water table depth of 35 cm (14 in.) in sand, 70 cm (28 in.) in fine sand, and 85 cm (33 in.) in a clay, the power of supplying water to the upper limits of the soil by the water table was negligible. Other investigators[6,7] show that for short periods of time (less than about 5 days) the capillary rise above a water table is generally less than 60 cm (24 in.) for all soils.

30. Fig. 3 shows the relations between moisture content of the 6- to 12-in. soil layer and water table depth and tension for a silt loam soil in Oregon. Data were taken during the winter and spring seasons. The graph shows that soil moisture losses were in accordance with soil moisture tension data until a water table depth of approximately 15 in. was reached; below this depth the actual moisture values began to diverge from the theoretical. A decrease in moisture content from 24 to 17 percent corresponded to a drop in the water table from 36 to 43 in.; to explain this moisture loss on the basis of tension, the water table would have had to drop approximately 130 ft (5000 cm - 1000 cm ≈ 130 ft). It is obvious, therefore, that at depths exceeding approximately 36 in., the water table did not contribute appreciable amounts of moisture to the 6- to 12-in. soil layer.
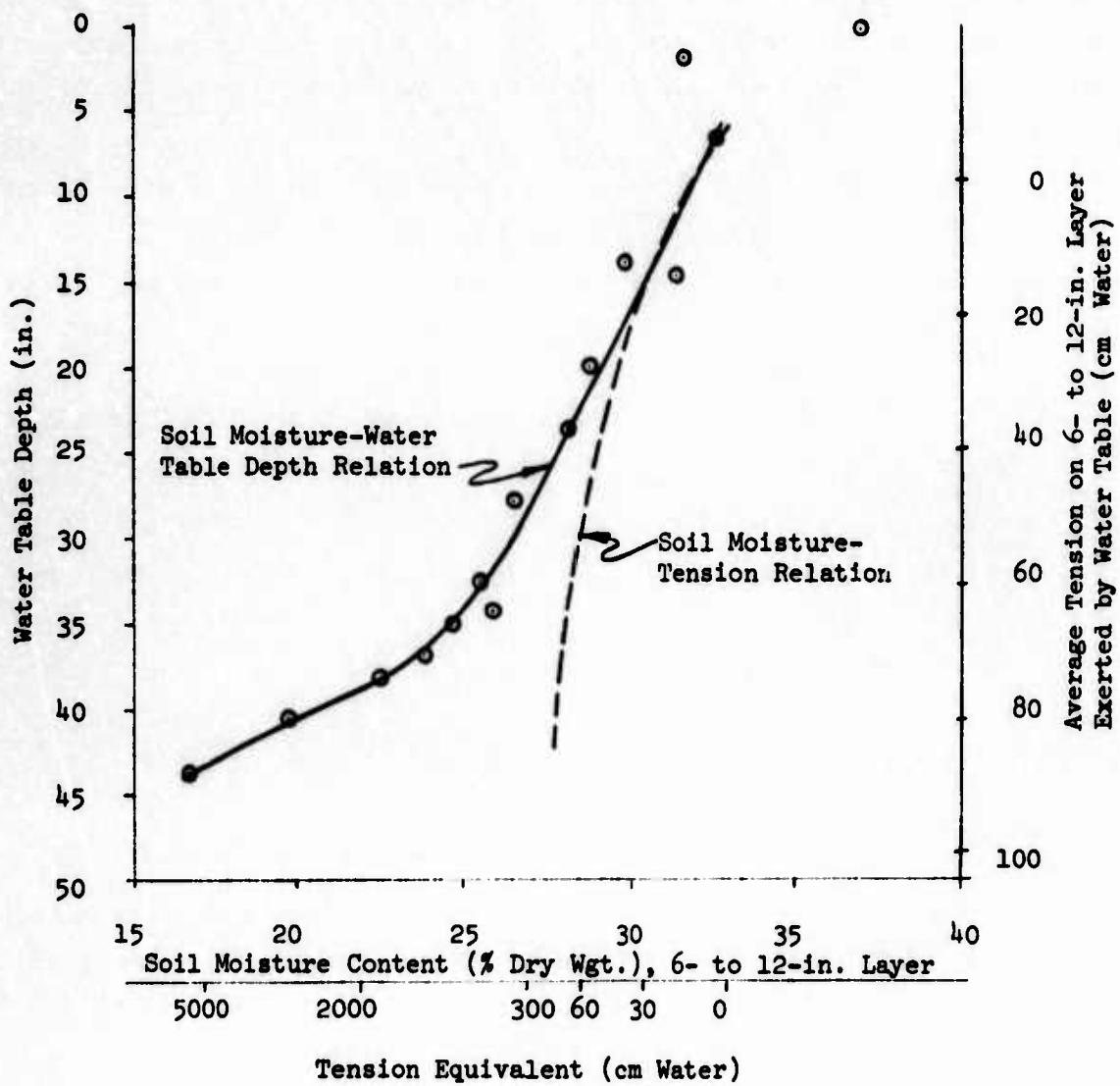
Fig. 3. Soil moisture relations with water table depth and
tension. Oregon site 228, 6- to 12-in. layer

31. The transfer of water from a water table to the 6- to 12-in. layer must be considered if accurate soil moisture predictions are to be made. In the Arkansas study, transition season (spring) depletion rates were applied during the summer months if a water table was within 36 in. of the soil surface to offset the effects of capillarity.

Soil Strength

32. Data from previous WES studies have shown that for a given fine-grained soil or sand with fines, poorly drained, rating cone index (RCI) decreases with an increase in moisture content. Furthermore, the relation can be defined by a smooth curve. An analysis of data from the three water-table studies tends to substantiate these conclusions.

33. Fig. 4 is a typical plot of RCI versus water table depth. As shown, RCI decreases to a minimum when the water table is close to the surface and remains constant with a further rise in the water table. The plots of data from many other sites also show a decrease in RCI to a constant minimum value. Minimum RCI values for these sites range from about 15 to 80, a range of maximum importance insofar as vehicle mobility is concerned.
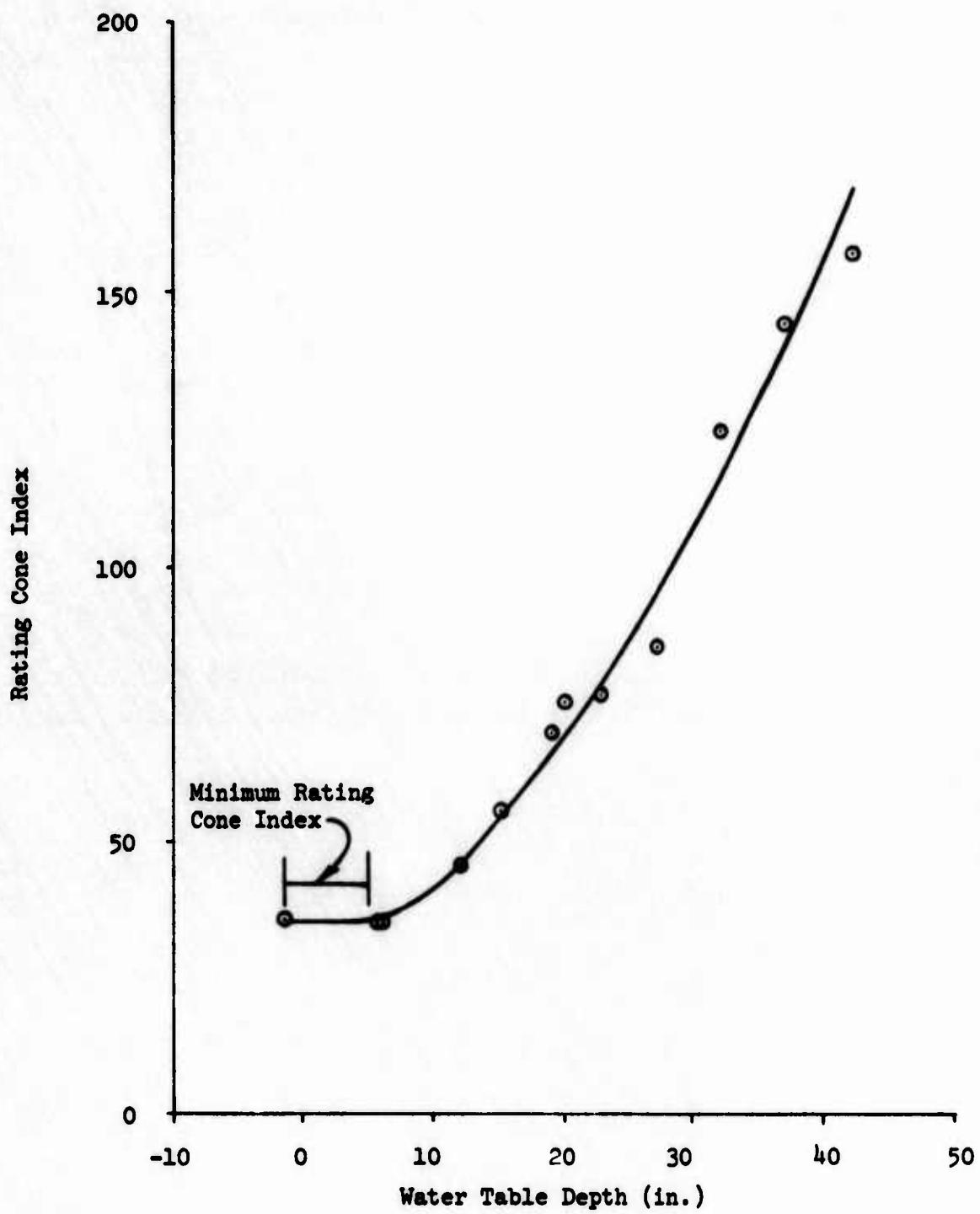
Fig. 4.   Rating cone index versus water table depth; Oregon site 226

PART III: FACTORS INFLUENCING THE INCEPTION, ACCRETION, AND RECESSION OF WATER TABLES

34. The factors found to have an influence on the inception, accretion, and recession of high water tables are discussed in this section of the paper. From a knowledge of the quantitative relations between the three water table characteristics noted above and all the factors which influence them, water table levels can be predicted. Unfortunately, some of the relations discussed herein are qualitative and do not easily lend themselves to the making of predictions. They are of importance, however, in that they can be used in the design of future water table prediction studies.

Inception

35. An analysis of data from the Arkansas and Oregon studies indicated that factors having a major influence on the inception of water tables were precipitation, topographic position, and soil stratification.

Precipitation

36. For each site of the Arkansas study, the cumulative rainfall after 1 October required to initiate a water table at maximum well depth (1 to 4 ft from the soil surface) was computed for the 1959-60 and 1960-61 wet seasons. For each site of the Oregon study, the cumulative rainfall after 1 September required to initiate a water table at depths of 24 or 7 in. from the surface (24 in. for nonclay pan soils and 7 in. for clay pan soils) was computed for the 1963-64 and 1964-65 wet seasons. In the Arkansas and Oregon study areas October and September, respectively, are the months during which the soil moisture normally begins to be recharged.

37. The data, 1959-60 versus 1960-61 for the Arkansas sites and 1963-64 versus 1964-65 for the Oregon sites, are plotted in fig. 5. The graphs show that the cumulative rainfalls required to produce high water tables are similar for two successive years (the points tend to fall on the lines of equality). This suggests that cumulative rainfall can be used to estimate the inception date of a water table.

Fig. 5. A comparison of rainfalls required to initiate a water table for two successive years

38. Because of differences in climate from one year to another, re-charging of soil moisture does not necessarily begin on the same day or even within the same month each year. Therefore, additional computations were made for the Oregon study. Rainfall was cumulated after the last day in the fall for which the moisture content of the 6- to 12-in. soil layer was near the field minimum moisture content. Soil moisture records indicated that for most of the sites these dates were approximately October 20, 1963, and October 27, 1964. The data are summarized in table D1.

Table D1

Cumulated Days and Rainfall Required to
Initiate a Water Table, Oregon Study

Water Table to Depth of 24 in. Nonclay Pan Sites					Water Table to Depth of 7 in. Clay Pan Sites				
	1963-64		1964-65			1963-64		1964-65	
Site No.	Days	Rain in.	Days	Rain in.	Site No.	Days	Rain in.	Days	Rain in.
226	63	12.1	43	10.8	227	26	7.4	31	7.6
228	26	7.2	31	7.6	230	26	7.6	34	8.9
229*	29	8.4	--	--	232	26	7.5	31	7.8
231	74	13.1	54	13.0	235	26	7.6	35	9.1
233	55	11.0	42	10.6	237	26	7.6	33	8.5
234	85	15.7	55	14.3	238	35	9.2	40	10.4
236	79	14.8	55	13.4					
239	75	13.6	50	12.0					
240	37	9.5	46	11.6					
Average rain/site required to initiate water table in 1963-64 and 1964-65			11.9						8.3

* No 1964-65 data available for site 229; 1963-64 data for this site not used in computing averages.

39. The average differences of cumulated rainfalls between years for dates of 20 October and 27 October, respectively, were only slightly smaller than those based on cumulations beginning on 1 September. Of interest, how-ever, is the fact that for a given site the cumulated rainfall was, in

most cases, markedly greater for the year in which cumulated days required for initiation of the water table was greatest. This is logical because soil moisture loss (through evapotranspiration and seepage) is related to time. The average loss amounted to 0.08 in. of water per day.

40. The factors of rainfall intensity and duration undoubtedly have an effect on water table inceptions. Analyses of these factors, other than the one discussed above, were not made.

Topography

41. The effect of topography on the inception of water tables was examined in the Arkansas study. The cumulative rainfall data for all sites of each topographic position shown in fig. 6 were averaged; results were as follows:

Topographic Position	Average Cumulative Rainfall, in., for Inception of Water Tables
Upland flat	10.0
Crest of slope	15.7
Upper slope	17.5
Midslope	16.7
Bottom of slope	10.0
Minor bottomland	10.7
Major bottomland	5.0

Between-site differences in cumulative rainfall required to initiate a water table were relatively large within some topographic positions. Regardless, the data indicate that topography is related to the inception of water tables.

Soil stratification

42. It would generally be assumed that shallow, relatively impermeable soil layers or horizons would influence water table inceptions. In the Arkansas study, attempts were made to determine the influence of fragipans on the inception of water tables. No relations were found, probably because there was some question as to the presence of and depths to the fragipans at some sites.

43. Data from the Oregon study, however, indicated that pronounced textural B horizons have a definite effect. The data included in table 1 show that, in general, much more rainfall was required to produce a water table on nonclay pan soils than on clay pan soils.

D16

Upland Flat

Crest of Slope
Upper Slope
Mid Slope
Bottom of Slope
Minor Bottomland

Crest of Slope
Upper Slope
Mid Slope
Bottom of Slope
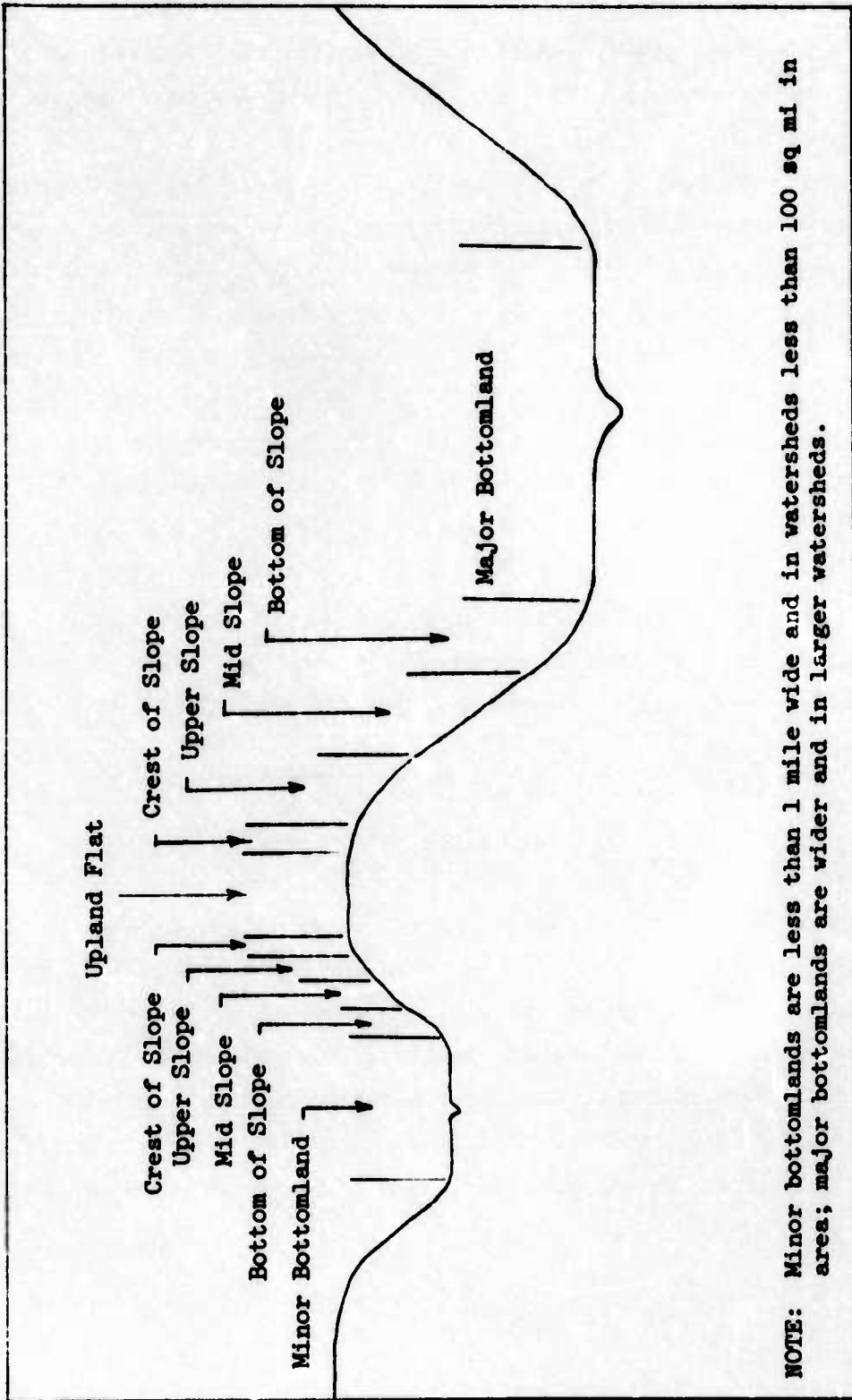
Major Bottomland

NOTE: Minor bottomlands are less than 1 mile wide and in watersheds less than 100 sq mi in area; major bottomlands are wider and in larger watersheds.

Fig. 6. Topographic positions along a profile

D17

44. Two factors, precipitation and pore-size distribution, were found to have an appreciable effect on the accretion of water tables.

Precipitation

45. For most sites it was found that under moist soil conditions water table accretions were closely related to precipitation. Furthermore, for sites with water tables within a few feet of the soil surface (2 or 3 ft for the Oregon study sites), the water table accretion-rainfall relation could be adequately defined by a straight line; an example is shown in fig. 7. Between-site differences in accretion relations must be due to differences in soil and site characteristics.

46. For one site in the Arkansas study, local precipitation had little effect on water table fluctuations. This site was located in a major bottomland about 1/2 mile from the Ouachita River. Water table levels were closely related to the river stage which, of course, was dependent primarily upon climatic factors many miles upstream. At sites located near secondary streams, water table accretions were closely related to rainfall.

Pore-size distribution

47. Soil pore-size distribution is a factor which affects water-table accretion relations. Generally, pore-size distributions are such that under moist conditions the volume of voids not occupied by water increases with increases in soil grain size. Thus, discounting differences in infiltration capacities, water table rises for a given amount of rainfall are greatest for clay soils; this was shown by Ward[8] to be the case in a study of water tables near Reading, England. The volumes of pores larger than those capable of holding water at 0.06-atm tension were related to differences in accretion-rainfall relations in a study of the Oregon data by Watts and Boersma.[4] It was also used as a factor in predicting water table levels for the Arkansas study sites.

Recession

48. As used herein, a recession refers to an increase in depth to
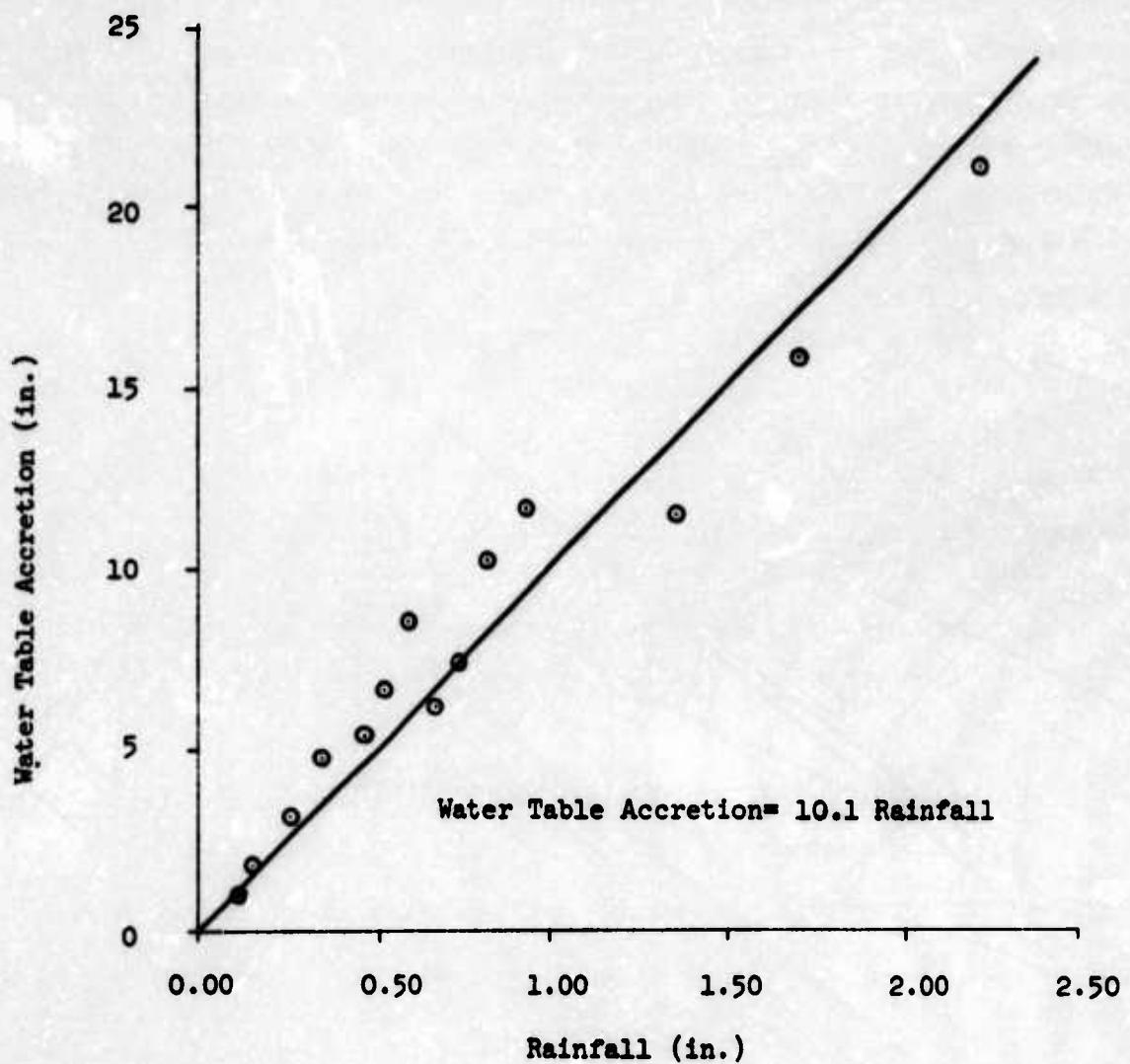
Fig. 7. Water table accretion-rainfall relation; Oregon site 240

D19

the water table and not to a loss of a volume of water. Four factors were found to have an effect on water table recessions. These were soil permeability, topography, soil pore-size distribution, and evapotranspiration.

49. The recession of a water table is also related to time. A water table recession-time relation can be constructed from a record of water table depths for nonrain periods during a given season; winter and spring recession-time relations for an Oregon site are shown in fig. 2. For given depth increments, the relation can be expressed as a rate, i.e. inches recession/day. Within-site and between-site differences in recession rates are affected by the factors discussed in the paragraphs that follow.

Soil permeability

50. Soil permeability measurements were not made in any of the studies. However, it is known that the clay pans which existed at some of the sites included in the Oregon study are relatively impermeable. A comparison of water table records showed that recession rates were markedly slower for clay pan soils than for nonclay pan soils.

Topography

51. Data from the Arkansas study demonstrated the effect of topography on recession rates. Monthly average recession rates for different topographic positions were as follows:

Topographic Position	Monthly Average Recession Rates, in.				
	Feb	Mar	Apr	May	Avg
Upland flat	1.40	1.40	1.90	2.90	1.90
Crest of slope	1.60	1.75	2.25	2.90	2.10
Upper slope	1.15	1.45	2.30	3.50	2.10
Midslope	2.30	2.50	3.20	5.00	3.25
Bottom of slope	0.80	1.10	1.30	1.80	1.25
Minor bottomland	0.70	0.70	1.00	2.30	1.20
Major bottomland	0.40	0.20	0.90	1.80	0.80
Average	1.20	1.30	1.85	2.90	1.80

Between-site differences in monthly average recession rates were large within some topographic positions. The data do, however, indicate that recession rates are related to topography.

Pore-size distribution

52. Soil moisture tension and water table recession data were analyzed for Oregon site 240. From the analysis it was determined that the

volume loss rate of soil water through seepage decreased with an increase
in depth to the water table. However, as shown in fig. 2, the recession
rates increased below a depth of 50 in. This was due to a decrease in the
volume of large pores with an increase in depth.

Evapotranspiration

53. Evapotranspiration does not affect water table recession rates
significantly during the winter months because vegetation is dormant or dead
and the rate of evapotranspiration is low. In the spring and summer,
however, appreciable amounts of water are removed from the soil by evapo-
transpiration. Laliberte and Rapp[9] showed that for a glacial till loam
soil near Alberta, Canada, evaporation influenced recession rates to a
water table depth of approximately 3 ft. The depth to which water table
recession rates are influenced by transpiration is dependent upon the
depth of rooting by vegetation.

54. The monthly average recession rates for the Arkansas study sites
are shown in paragraph 51. The average rate was more than twice as great
in late spring (May) as it was in the winter (February). The increased
rate of recession was due to increased water losses through evapotranspira-
tion. Similar increases in recession rates due to evapotranspiration were
also noted in data from the Oregon study. An example is shown in fig. 2.

PART IV: A TENTATIVE WATER TABLE CLASSIFICATION SCHEME

55. A tentative water table classification scheme was developed from data of the Mississippi-Alabama study. The scheme included five classes; the classes were differentiated according to the percentage of time that a water table existed within specified soil depth increments during the winter and spring seasons. Soil depth increments used were 0-1 ft, 1-4 ft, and 4 ft plus. Classes and the criteria for separating classes are presented graphically in fig. 8.
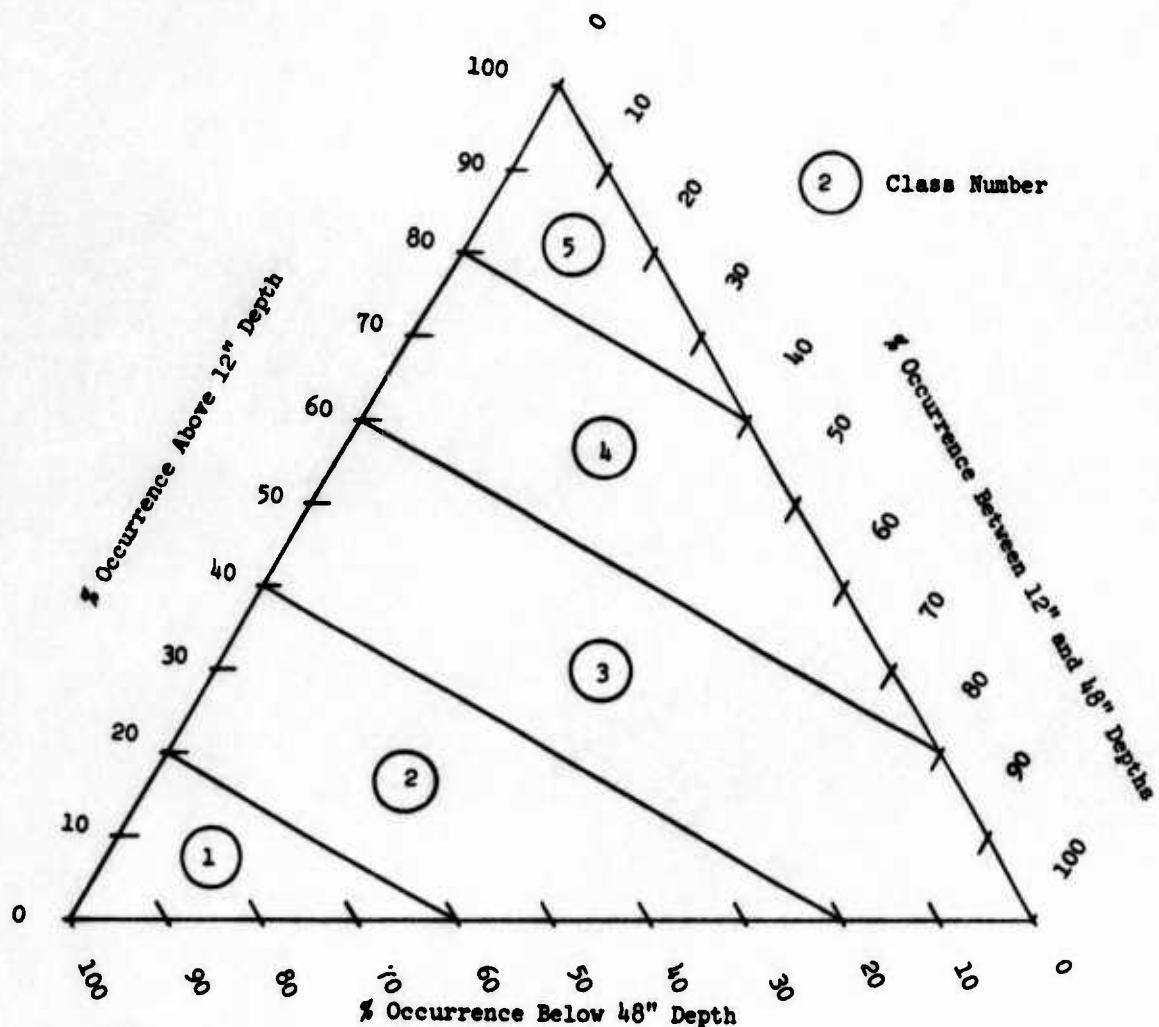

Fig. 8. A tentative, wet season water table classification scheme

56. The classes are numbered 1 through 5; class 1 sites are least subject to high water table conditions, and class 5 sites are most subject to such conditions. Since the scheme was designed to separate sites on the basis of frequency of occurrence of very wet soil conditions, it was not illogical to test the effectiveness of the scheme in separating sites on the basis of soil strength. The average rating cone index for the wet season was computed for each of the Mississippi-Alabama study sites at which soil strength data were obtained and the data were averaged by classes. A summary of the results follows:

	Water Table Class				
	1	2	3	4	5
Number of sites	1	1	7	7	8
Average rating cone index	118	165	119	65	47

Soil type differences were not considered, and variations within classes 3, 4, and 5 were large. The values for classes 1 and 2 were each based on data for one site and therefore should not be considered reliable averages. Nevertheless, the data do indicate a general trend, i.e. RCI increases with a decrease in class number.

57. Data from both the Mississippi-Alabama and Arkansas studies were examined to determine whether associations exist between class numbers and topography. To obtain good resolution, it was necessary to consider shallow, relatively impermeable soil layers. Results are shown graphically in fig. 9. In essence, the data show that wetness is closely related to local topography, perched water table conditions, and the level of water in local stream channels.
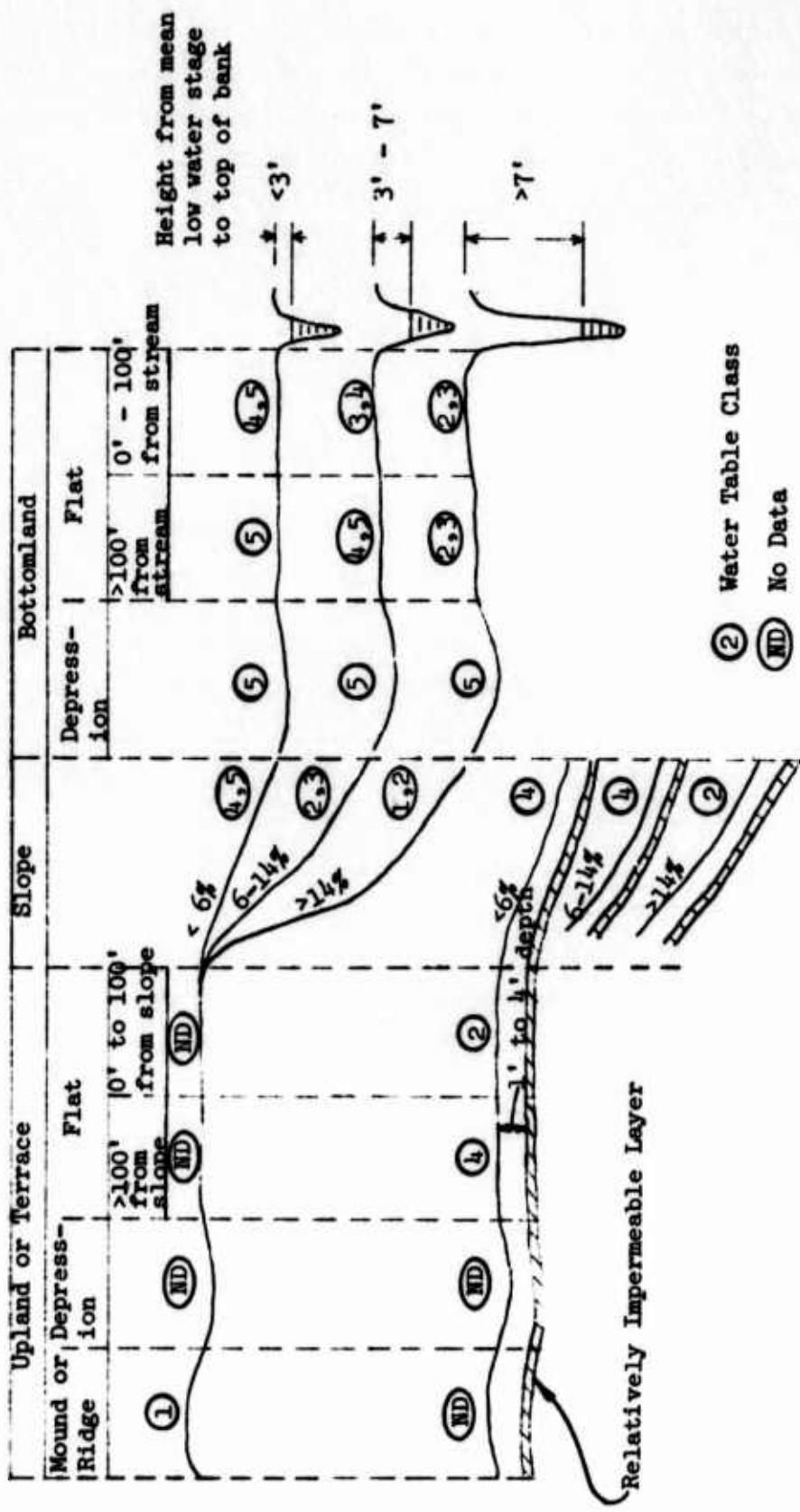
Fig. 9. Water table classes as they relate to terrain and soil characteristics

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APPENDIX E: INFLUENCE OF SOIL VARIABILITY ON SOIL MOISTURE AND SOIL STRENGTH PREDICTIONS

by

H. D. Molthan

Contents

Introduction

1. A primary problem common to all sciences dealing with soils is
that of adequate measurement of a soil's physical, chemical, and mineral-
ogical characteristics. There are two basic causes for this problem: first,
the inadequacy of methods for measurement, and second, the nonhomogeneity of
soils. The discussion herein will be limited to the latter as the purpose
of this report is to discuss the results of four studies reporting soil
variability, the effects of this variability on soil moisture and soil
strength prediction, and the number of samples necessary to obtain a re-
liable estimate of the various static and dynamic soil properties that are
used to predict soil trafficability.

Soil Variability Data

2. Because each of the studies reviewed herein is unique with re-
spect to objective, method of investigation, and presentation of data, the
pertinent results of each study will be reviewed briefly.

3. Bassett, McDaniel, and Knight[1] reported the results of sampling
65 sites, representing four different soil series, all developed from a
uniform loess parent material and possessing similar morphological character-
istics. A statistical analysis of data relating to physical characteristics
of the soils, i.e. grain-size distribution, Atterberg limits, dry density,
etc., revealed that none of the sites was significantly different from the
others. All sites were sampled once during the wet season when the soil
moisture was near field capacity. Four moisture-density samples, four re-
molding index measurements, and twelve cone index measurements from the 6-
to 12-in. depth were taken at each of the 65 sites. Also, four bulk samples
were taken and composited for laboratory analysis.

4. The mean standard deviations and mean coefficients of variation
by soil series and for all sites grouped are as follows:

Soil Characteristic	Mean Standard Deviation		Mean Coefficient of Variation, %	
	By Soil Series	All Sites Grouped	By Soil Series	All Sites Grouped
Cone index	42	43	36	36
Remolding index	0.12	0.13	25	27
Rating cone index	30	30	51	51
Moisture content, %	3.0	3.3	12	13
Dry density, pcf	4.6	4.8	5	5
Liquid limit	4	4	14	14
Plastic limit	1	1	6	5
Plasticity index	3	3	45	43
Grain-size distribution*	6	6	7	7

* Unified Soil Classification System fines.

A comparison of the data shows no meaningful differences in the variation of data whether the sites are grouped by soil series for analysis or analyzed as one sample population. If the strength data are grouped in 2% increments of moisture content (the moisture range is from 19.5% to 34.1% with 80% of the sites between 21% and 29%) the mean standard deviation of the cone index is reduced to 27 and the mean coefficient of variation to 23%.

5. Carlson and McDaniel[2] selected 24 test sites specifically for the purpose of testing soil variability. The soil at all sites was developed from a uniform loess parent material. However, half of the sites were located on upland soils that had developed in place, and the other half were located in alluvial valleys where the soils had developed in outwash from the adjacent loessial hills. Each site was 30 ft wide and varied in length according to the width of the soil mapping unit in which it was located (approximately 300 to 500 ft). Five equidistant rows were marked at each site and all samples were taken along these rows. The static properties of the soil, i.e. grain-size distribution, Atterberg limits, specific gravity, etc., where sampled only once at each site. Cone index, remolding index (when possible to test), density (when possible to test), and moisture content (% dry weight) were determined on each of four visits

to the site. On each visit all sites were sampled in one day to ensure as much climate uniformity as possible. In all, approximately 1000 cone index, 200 remolding index, and 850 moisture measurements were made.

6. For statistical analyses the soils were grouped morphologically (by soil series), topographically (upland or bottom land), and by sampling row. The soils could not be separated statistically as to morphology on the basis of the physical properties measured in this study and the only statistically significant differences topographically were the lower clay content and lower plasticity of the bottom lands. The mean standard deviations and mean coefficients of variation for both the 0- to 6-in. and 6- to 12-in. depths are as follows:

Soil Characteristic	Depth in.	Mean Standard Deviations		Mean Coefficient at Variation, %	
		By Site	By Row*	By Site	By Row*
Cone index	0-6	60	32	35	18
	6-12	90	46	34	18
Moisture content, %	0-6	2.0	2.0	7	7
	6-12	3.1	1.6	8	6
Dry density, pcf	0-6	2.5	2.0	3	2
	6-12	1.2	1.6	1	2
Liquid limit	0-6	3.1	3.1	9	9
	6-12	3.8	3.4	11	8
Plastic limit	0-6	1.5	--	6	--
	6-12	1.3	--	5	--
Plasticity index	0-6	2.8	3.0	28	32
	6-12	3.5	3.4	35	24
Grain-size distribution**	0-6	1.1	--	1	--
	6-12	1.5	--	2	--

* All sampling rows containing an inclusion of a different soil series were omitted from analysis. These rows are responsible for the larger standard deviations when data were grouped by site. However, it must be remembered that small inclusions of a different soil within a larger relatively uniform soil mass are not uncommon. Also, these areas are not normally delineated on standard soil survey maps.

** Unified Soil Classification System fines.

A comparison of the cone index data for the 0- to 6-in. and 6- to 12-in. depths shows similar coefficients of variation, indicating that the larger standard deviations for the 6- to 12-in. depth were due to the greater mean strength for that depth. Data were insufficient for a meaningful analysis of remolding index and hence rating cone index. However, the standard deviation and coefficient of variation for remolding index, based on all 200 sample points, were 0.20 and 39%, respectively.

7. Carlson and McDaniel[2] concluded that the large variation in soil strength was due primarily to differences in the reception and retention of water, and secondarily to differential erosion and deposition and the associated differences in soil structure and organic content.

8. Lull and Reinhart[3] reported the variability of soil moisture from eight study sites. The sites, each 200 by 200 ft, were located in six states, with two sites each in Mississippi and Colorado, and one site each in Arkansas, Louisiana, New Mexico, and Wisconsin. Eight moisture samples from both the 0- to 6-in. and 6- to 12-in. depths were taken at random from each site weekly during the study period. The study continued for 6 months, 3 in the wet season and 3 in the dry season, except for sites in Colorado and Wisconsin which were sampled for only one 3-month period. The standard deviation and coefficient of variation were determined for each weekly sampling of each site. The mean standard deviations and mean coefficients of variation for each site by season and for the entire study period are as follows:

Site	Depth in.	Mean Standard Deviation, in. Season			Mean Coefficient of Variation, % Season		
		Dry	Wet	Both	Dry	Wet	Both
Louisiana	0-6	1.1	2.5	1.8	6	8	7
	6-12	1.9	2.4	2.2	9	7	8
Mississippi 1	0-6	4.2	3.1	3.6	23	10	17
	6-12	3.6	1.7	2.6	19	6	12
Mississippi 2	0-6	1.6	1.9	1.8	18	7	12
	6-12	2.6	2.9	2.8	20	10	15
Arkansas	0-6	2.0	2.5	2.2	20	10	15
	6-12	2.0	1.9	2.0	23	7	15

(Continued)

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Site	Depth in.	Mean Standard Deviation, in. Season			Mean Coefficient of Variation, % Season		
		Dry	Wet	Both	Dry	Wet	Both
New Mexico	0-6	1.7	2.5	2.1	19	11	15
	6-12	1.5	2.7	2.1	13	14	14
Colorado 1	0-6	1.6	--	1.6	15	--	15
	6-12	1.9	--	1.9	17	--	17
Colorado 2	0-6	--	5.7	5.7	--	47	47
	6-12	--	4.1	4.1	--	38	38
Wisconsin	0-6	3.5	--	3.5	18	--	18
	6-12	4.1	--	4.1	22	--	22
All sites	0-6	2.2	3.0	2.6	17	16	16
	6-12	2.5	2.6	2.6	18	14	16

9. It was concluded that the variation in moisture measurements within a given site was primarily caused by differences in the type and amount of vegetative cover, depth to water table (if one was present), and the degree of moisture saturation, e.g. the higher the moisture content the greater the absolute deviation, of the soil when the measurements were made.[3] For example, the site with greatest variation, Colorado site 2, had only a 5% to 10% cover of short bunch grasses and the remainder of the site was bare. The Louisiana, Mississippi, Arkansas, and New Mexico sites were well covered with vegetation and Colorado 1 site was only 25% bare. The standard deviations for the wet season measurements were greater than those for the dry season at four of the five sites for which these data were available. The one exception, Mississippi site 1, had a water table near the surface of the site during the wet season study period. This probably accounted for a more uniform wetting of the soil at this site.[3] However, the mean coefficients of variation were less for the wet season than for the dry season for all sites except the Louisiana site where they were approximately equal. It appears, as will be discussed later, that from a trafficability standpoint the coefficient of variation is probably more significant than the standard deviation in measuring the variation of soil strength and factors affecting it.

10. Meyer,[4] in his report on engineering properties of tropical and temperate soils, reported the physical properties of the soils at

11 temperate and 17 tropical study sites. The sites were visited once and 20 measurements of cone index, remolding index (when possible to test), moisture content, and dry density (when possible to test) were made. Also, 20 bulk samples were taken from each site for laboratory analysis of Atterberg limits. The standard deviations and coefficients of variation for each of the measurements were computed for each site. The mean values for all sites grouped by climate were as follows:

Soil Characteristic	Mean Standard Deviation		Mean Coefficient of Variation, %	
	Temperate Soils	Tropical Soils	Temperate Soils	Tropical Soils
Cone index	37	48	18	18
Remolding index	0.14	0.14	16	16
Rating cone index	48	56	24	25
Moisture content, %	3.3	2.4	7	6
Dry density, pcf	4.2	4.8	5	6
Liquid limit	5	5	6	6
Plastic limit	2	2	6	4
Plasticity index	4	4	13	11

11. A comparison of the data for temperate and tropical soils shows no meaningful difference in variation for each of the measured soil properties. The standard deviations of cone index, rating cone index, and dry density are slightly higher and the standard deviation of moisture content slightly lower for tropical soils. However, the coefficients of variation are almost the same, indicating that the small differences in standard deviation can be attributed to differences in the average means of these properties.[4]

12. It is difficult to compare results of these different investigations because different sized sites were used and different methods of data grouping and analysis were employed. However, three of the studies did report variance on the basis of replicate measurements taken at a given site at the same time.[2,3,4] Unfortunately, one study used sites approximately 100 sq ft in area that were visited only once, another used sites approximately 10,000 to 15,000 sq ft in size each visited four times,[2] and the

third used sites 40,000 sq ft in area nearly all of which* were visited 28 times.[3] The resulting coefficients of variation in measurements of soil strength and soil moisture increased as the size of the site and number of visits increased. The remaining study[1] reported only site averages, and data were grouped by soil series with from 15 to 21 sites representing each of four soil series. The only other common factor in this grouping was that all sites were sampled during the wet season when high moisture conditions prevailed. Therefore, variation in this instance was not the variation among replicate samples, but the variation among different sampling areas of a recognizable soil series sampled under a similar climatic environment. The resulting variations in the dynamic properties of the soil, moisture and strength, were large but variations of the static properties of the soil were small.

Discussion of Soil Variability

13. All soil moisture and soil strength prediction schemes currently used at WES depend in some way on taking soil measurements at time t_i and point x_i and using these values to make a prediction or estimation of what the soil moisture or soil strength will be under the same or a similar set of environmental conditions. It is obvious that no physical property of the soil can be predicted with greater accuracy than it can be measured. However, it is recognized that if an area has a very high average soil strength a relatively large variation in the measurement of that strength will have little effect on the usefulness of trafficability predictions made from those data. Therefore, this discussion will be limited to those times and places when and where the strength of the soil is critical to trafficability and an accurate knowledge of strength is necessary. Under these conditions, the source and magnitude of the variation exhibited in measurements of various soil properties must be understood before the reliability and usefulness of any prediction scheme attempting to predict the full range of soil strength can be properly evaluated.

14. It is conceded that errors in sampling and measurement as well

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* Three sites visited only 14 times.

as natural variability of the soil contribute to the variation in replicate measurements of various soil properties. However, it is believed from experience and a study of the limited amount of applicable data available that the errors in sampling and measurement can be kept small with respect to total variation. For this reason it will be assumed that the variations in the soil measurements reported in these studies resulted primarily from variations of the soil.

15. Having made the foregoing assumption the next logical step is to ascertain the nature and source of this variability in soil. Is soil variability due to point to point horizontal variation within a large relatively homogeneous soil area, is it the result of an apparently homogeneous soil province containing relatively large (large when compared to a sampling point) anomalies, or what? This point is extremely important because the problem of properly analyzing and characterizing any particular soil province is dependent upon it. If soil variability is primarily the result of point to point variation, then all that is necessary to properly characterize a particular soil property is to ascertain the number of samples necessary for a statistically significant estimation of that property. If the source of variation is from anomalous areas, additional problems arise. First the extent and frequency of occurrence of the anomalous areas should be established or estimated, then they should be characterized separately from the surrounding soil. This is especially true if these anomalous areas are larger in size than a vehicle trafficking the area. Also, the usefulness and value of any predictions or estimations based on data of doubtful reliability and containing unknown sources of variability are greatly reduced. It can make considerable difference whether an area is trafficable 75% of the time or 75% of the area is trafficable any time.

16. Lull and Reinhart[3] have possibly shed some light on this subject. Their large sites were equally divided into 4 blocks, each block was divided into 4 equal-sized plots, and each plot divided into 25 equal-sized sampling squares. In their statistical analysis of the resultant data the variance between replicate samples was partitioned into three components: between squares within a plot, between plots within a block, and between

blocks. As a result, 67% of the variance was found to be between sampling squares, 20% between plots, and 13% between blocks. However, if the data from Mississippi 1 site, where a large portion of the variance is between plots, are omitted, the resulting partition of variance becomes: 74% between squares within a plot, 13% between plots within a block, and 13% between blocks. Unfortunately, not enough samples were taken within each square to determine the proportion of variance between samples within a square. If the trend expressed by these data, that the greatest portion of the total variance is associated with the smallest sampling subdivision, can be validly extrapolated to sample points, it would appear that most of the variation found in measuring the soil moisture of these sites was point to point variation, the Mississippi 1 site being the exception. Carlson and McDaniel[2] by careful field examination found definite anomalous soil inclusions within their study sites and reanalyzed their data after ex-cluding all data from these areas. This reduced the resultant standard deviations and coefficients of variation for soil strength and moisture by almost half. From the data given in these reports and from a purely morpho-logical standpoint it would appear that both types of variation are present in many soil provinces, the point to point variance being ubiquitous and the variability arising from the inclusion of anomalous areas in many if not most soils. However, the proportion of variance due to each probably varies greatly.

Number of Samples Necessary for a Reliable Estimate

17. It can be shown statistically that the means $\bar{x}_i$ of several different subsamples taken from a sample population possessing a mean μ_x and a standard deviation σ_x , even if that population is not normally distributed, will be normally distributed with a mean $\mu_{\bar{x}}$ and a standard deviation $\sigma_{\bar{x}}$, where

$$\mu_{\bar{x}} = \mu_x \tag{1}$$

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$$\sigma_{\overline{x}} = \frac{\sigma_x}{\sqrt{n}} \qquad (2)$$

if n , the sample size, is sufficiently large. The size of n necessary for a reasonable approximation to equations 1 and 2 is dependent on how far the distribution of the sampled population deviates from normal. If the true value or a reasonable approximation of σ_x is known, an estimate of μ_x , within predetermined limits and possessing a given probability of success, can be obtained by using as that estimate the sample mean $\mu_{\overline{x}}$ of a subsample of size n , where

$$n = \left[\frac{t(\sigma_x)}{L}\right]^2 \qquad (3)$$

with t being the probability factor and L the allowable error.

18. In calculating the sample size necessary for an accurate estimation of the true sample mean from the variability data reported herein, the allowable error was expressed as a percentage of the sample mean rather than an absolute value. The reason for this was that from a trafficability standpoint the lower the strength of a soil the greater the accuracy with which it must be known. A standard deviation of 40 units would not be of great importance if the mean cone index is 200, but would render a mean cone index value of 60 completely useless in predicting trafficability. Also, the relation between soil moisture and strength is exponential and the slope is much less at the high moisture-low strength end of the curve. Therefore, the same error in the estimate of soil moisture will result in a much smaller error in the prediction of soil strength at the wet end of the moisture-strength curve than at the dry end. In general, as the absolute value of a particular measurement increases the tolerable amount of variance increases also. For this reason and for consistency all sample sizes were calculated on the basis of an allowable error expressed as a percentage of the mean.

19. An allowable error of 10% of the mean was arbitrarily chosen for the strength measurements and Atterberg limits, and an error of 5% of the mean for moisture content, dry density, and grain-size distribution. This necessitated changing equation 3 to the form

$$n = \left[\frac{t \text{ (coefficient of variation)}}{L} \right]^2 \tag{4}$$

where L is expressed as a percentage of the sample mean.

20. Table E1 gives the number of samples necessary for obtaining a sample mean $\mu_{\bar{x}}$ within the expressed allowable limits of the true mean μ_x at both the 80% and 95% confidence levels for the data reported in each of the studies reviewed herein. It will be noted that the number of samples calculated for determination of the static soil properties does not vary greatly with the source of data, but those calculated for soil moisture and soil strength determinations do. It would appear from these data that to effect a reasonable approximation to the true value of soil moisture or strength one needs to know the type of variability expressed in the measurements. For example, note the significant reduction in sample number when the data reported by Carlson and McDaniel[2] were reanalyzed to remove the variance from detected anomalous soil areas. Also, note the large difference in the results of the data from large sample areas, where inclusions of anomalous soil areas are more likely, and the data reported by Meyer[4] from small-sized sampling sites. From these data it would appear that if the variance is primarily due to point to point variation one would need only 5 to 10 measurements of strength or moisture content, but if anomalous soil areas are a major contributor to the soil variability then at least 20 measurements are necessary for soil strength and approximately 10-15 for soil moisture. However, estimating the number of samples necessary to accurately express the numerical value of a particular soil property appears premature at this time. It must be remembered that the validity of all the above calculations, as they are applicable to characterizing a particular area for soil trafficability, depends upon the measured variance being due to random sources. One thousand samples would not give a useful mean value of soil strength if most of the area had a cone index above 100 but the remainder of the area, represented by relatively small anomalous areas, had a cone index of only 50. In utilizing statistical methods of analysis it is well to remember the following quotation, "Statisticians all over the world are drowning in streams with an average depth of only

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Table E1

Summary of Sample Sizes Necessary for Estimation of Site Mean Value of Soil Properties

Soil Characteristic	Depth in.	L* in %	Number of Replicate Samples									
			80% Confidence Level Source of Data					95% Confidence Level Source of Data				
			Ref. No. 1	Ref. No. 2 By Site	Ref. No. 2 By Row**	Ref. No. 3	Ref. No. 4	Ref. No. 1	Ref. No. 2 By Site	Ref. No. 2 By Row**	Ref. No. 3	Ref. No. 4
Cone index	0-6	10	--	20	5	--	--	--	47	12	--	--
	6-12	10	21	19	5	--	5	50	44	12	--	12
Remolding index	6-12	10	10	25	15	--	4	24	58	35	--	10
Moisture content, %	0-6	5	--	3	3	17	--	--	8	8	39	--
	6-12	5	9	4	2	17	2	22	10	6	39	6
Dry density, pcf	0-6	5	--	1	1	--	--	--	1	1	--	--
	6-12	5	2	1	1	--	2	4	1	1	--	6
Grain-size distribution	0-6	5	--	1	--	--	--	--	1	--	--	--
	6-12	5	3	1	--	--	--	8	1	--	--	--
Liquid limit	0-6	10	--	1	1	--	--	--	3	1	--	--
	6-12	10	3	2	--	--	1	8	5	2	--	1
Plastic limit	0-6	10	--	1	--	--	--	--	1	--	--	--
	6-12	10	1	1	--	--	1	1	1	--	--	1

* L is the allowable error.

** Data from those sampling rows containing anomalous soil inclusions omitted from analysis.

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eighteen inches."* This statement is particularly choice for paraphrasing in terms of soil trafficability.

Conclusions and Recommendations

21. While the data reviewed in this paper are of limited extent and applicability, some trends do appear in these data that seem worthy of discussion and further consideration. It is evident that there are large variations in the measurements of soil moisture and strength, especially the latter, and the nature and magnitude of the individual sources of variability contributing to this large variance are not well understood at present. From the limited data available, it would appear that point to point soil variance and the associated sampling and analytical errors in the measurements of soil properties are not large enough to cause great concern, but the variation arising from soil anomalies is excessively large. In one study, the coefficient of variation in replicate measurements of the cone index was reduced from 34% to 18% by excluding from analysis those sampling rows containing anomalous inclusions of a different soil.[2] An adequate means of recognizing, analyzing, and characterizing these anomalous areas appears to be necessary before the present methods of predicting soil moisture and strength can attain the accuracy necessary for predicting soil trafficability. Also, it appears that the magnitude of the soil variance is directly proportional to the size of the sampling area. This would add some doubt to the validity of measuring the soil properties of a small plot and extrapolating those values to a large soil area, even if that area is relatively homogeneous.

22. If a soil area is relatively homogeneous, containing no anomalous areas of appreciable size, a good estimation of the number of samples necessary to accurately characterize a particular property are approximately: 5-10 for soil strength, 3-8 for soil moisture, and 2 for the static properties of the soil. Unfortunately, properly characterizing the properties of a soil area that is not homogeneous is not so simple, and attempting to

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* Author unknown.

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ignore this nonhomogeneity by simply taking a large enough number of measurements to satisfy a statistical analysis is not the answer. Statistics, like the street lamp, should be used for light, not, as the drunk uses the lamp post, for support.

23. It appears that before satisfactory predictions, and perhaps even satisfactory measurements, of soil trafficability are possible a greater knowledge of the various sources and magnitudes of variation both within a given soil area and between different soil areas is necessary. Without this knowledge, how can the present soil moisture or soil strength prediction schemes be put to practical use, e.g. how can results obtained from a small site within a soil area be extrapolated to the whole soil area or be projected to analogous soil areas? To this end it is recommended that additional variability studies be initiated as part of the prediction program.

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**APPENDIX F: COMPARISON OF SOIL MOISTURE PREDICTION FACTORS
FOR TEMPERATE AND TROPICAL CLIMATES**

by

M. H. Smith

Contents

APPENDIX F: COMPARISON OF SOIL MOISTURE PREDICTION FACTORS FOR TEMPERATE AND TROPICAL CLIMATES

Introduction

Purpose

1. The purpose of this paper is to compare soil moisture prediction factors for temperate climates with those for tropical climates. The comparisons will be made against the background of a general description and comparison of the climate in the two climate zones.

Prediction factors

2. Since the moisture prediction method works on the principle of either increasing or decreasing the previous day's soil moisture content, the two primary factors to consider are: accretion relations and depletion relations. The flow diagram in fig. F1 shows how these and other factors in the prediction method operate with respect to each other. Rainfall above minimum storm and available storage (difference between moisture in the soil and the maximum it can hold) determine the accretion. Depletion is determined by the range from maximum to minimum moisture contents and by the time interval which is required to move from maximum to minimum during a no-rain period. Since this time interval varies with the season, season and transition dates between seasons are factors of depletion. In the temperate climate, estimates of field maximum and field minimum moisture contents were made. These estimates were based on soil texture, wetness index (an index of soil wetness), organic content, and the soil moisture under 0.06-atm tension. The equations for these estimates did not prove applicable to the tropical climate sites, so these secondary factors will not be considered here. The factors to be compared are:

      a. Seasons with transition dates.

      b. Daily rainfall.

      c. Minimum storm.

      d. Field maximum moisture content.

      e. Field minimum moisture content.

      f. Accretion relations.

      g. Depletion relations.

F1

General Description and Comparison of Climate Zones Studied

Location of studies

3. Fig. F2 delineates in a gross way the study areas in the temperate and tropical climates and their relation to the total area of the earth. The soil moisture prediction studies for the temperate climate have been conducted since 1951 at approximately 160 prediction development sites and 600 survey sites located in the United States and Alaska. Studies for the tropical climate have been conducted at approximately 80 prediction development sites and 300 survey or auxiliary sites located in Panama (2 studies), Puerto Rico (2 studies), Costa Rica (2 studies), Colombia, Hawaii, and Thailand. The shaded areas in fig. F2 indicate the approximate location of the sites. The encircled shaded areas are tropical sites. All study areas lie in the northern hemisphere and all, with the exception of Thailand, are in the western longitudes.

Climate

4. The temperate climate zones lie between the $23\text{-}1/2^{\circ}N$ and $66\text{-}1/2^{\circ}N$ latitudes in the northern and southern hemispheres. The climate of the temperate zone varies greatly. Average annual temperatures vary from 70 F in Florida and northern Mexico to 10 F in northern Canada (see fig. F3). The shaded areas of fig. F3 have temperatures appreciably different from that of the surrounding area and are not included in the averages. These areas are at elevations over 5000 ft and are present in both temperate and tropical climate zones.

5. The average annual rainfall in temperate climates is less than that of tropical climates. Fig. F4 shows large areas in the tropics with more than 60 in. of annual rainfall. In contrast the temperate climate zone has few such areas.

6. The tropical climate zone has an almost constant temperature except for the areas of high elevation. Grenke* places tropical climate

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* W. C. Grenke, Observing, Analyzing, and Forecasting the State of the Ground, U. S. Army Engineer Waterways Experiment Station CR No. 3-112, Vicksburg, Miss., May 1965. Prepared under contract by Wilson, Nuttall, Raimond Engineers, Inc.

geographically between 25°N and 25°S latitudes. In the following excerpt he describes tropical climate:

Climate

155. One of the basic influences on the humid tropical climate is the fact that the sun is always overhead somewhere as it migrates from Tropic to Tropic. The noon sun remains overhead or nearly so for one relatively long period each year near the Tropics, and for two relatively short periods near the equator. Thus, it is not surprising to find generally higher temperature maxima near the Tropics than nearer the equator. The mean monthly temperatures are fairly constant. The mean annual range of temperature is often less than 3 C (5.5 F), yet the diurnal range may be more than 10 C (18 F).

156. Many areas near the Tropics experience a rainy season shortly after the period of high sun, and many near the equator have two rainy seasons. However, this classical pattern is often offset by various regional and local factors. Humid tropical rainfall usually results from convectional or orographic causes rather than from cyclonic or frontal activity, although the latter is by no means nonexistent (hurricanes, for example). Because of this, short but intense rainfall often occurs in the afternoon, especially on or near mountain slopes where air masses rise abruptly.... When the winds are predominantly from one direction for long periods of time, the mountains may have "rain shadows," and rainfall differences of over 2500 mm (100 in.) per year may be found at relatively short horizontal distances. Rainfall can also vary appreciably with elevation. Mean rates of annual increase may exceed 250 mm per 30 m (10 in. per 100 ft). These variations make it extremely difficult to extrapolate rainfall data from rain gage stations, which are notably scarce in some humid tropical areas....

157. Another interesting feature of humid tropical rainfall is that the annual amount is usually greater, but the annual number of rain-days is often less, than for temperate latitudes. For example, contrast London (24 in., 167 rain-days) with Bombay, India (71 in., 75 rain-days), which has about three times as much rainfall in about half as many days, and with Menado, Celebes (104 in., 174 rain-days), which has about four times as much rainfall in about the same number of days.

158. This is indicative of the intensity of tropical

rainfall which will often average over 1/2 in. per rain-
day, as in the cases cited, and in fact be over 1/2 in.
per hour for reasons already mentioned. Hourly rates
of 2 in. or more may occur, but usually not more than
once a year.... Record rainfalls in the tropics
have exceeded 4 in. per hour. However, it is not meant
to imply that rainfall occurs only in short, intense
downpours. In some areas, especially those influenced
by the trade winds, light showers and drizzles may occur
throughout much of the year, as in Oahu, Hawaii, and
parts of Malagasy. In other tropical areas, intense
downpours may last longer than for just a few hours in
the afternoon. For longer periods of time, in the East
Indies for example, rainfall may reach 10 in. per day,
with records of 20 in. A final classic example of
tropical downpours is noted in the case of Cherrapunji,
India, which received 241 in. of rain in August 1841,
of which 150 in. fell on five consecutive days.*

159. The short, intense rains generally permit
more hours of sunshine per day. Compare London, which
has about 4 hours of sunshine on the average day, with
Georgetown, British Guiana, which has 6.8 hours, and
Singapore which has 6.1 hours.

160. Since mean monthly temperatures are relatively
constant in the humid tropics, mean monthly potential
evapotranspiration is also relatively constant, while
rainfall is often seasonal. In temperate regions, the
situation is often reversed. A classic example of this
is noted in the case of Medellin, Colombia, and Columbus,
Ohio, shown in figure 16. Diurnal variations are often
greater than monthly variations.

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* Most of the rainfall data presented in this section
have been cited from Beckinsale, R. P. "Nature of tropical
rainfall," Tropical Agriculture, 34 (2): 76-98, Trinidad,
W. I., Apr. 1957.

COLUMBUS, OHIO   MEDELLIN, COLOMBIA

→ potential evapotranspiration (inches per month)

→ precipitation (inches per month)
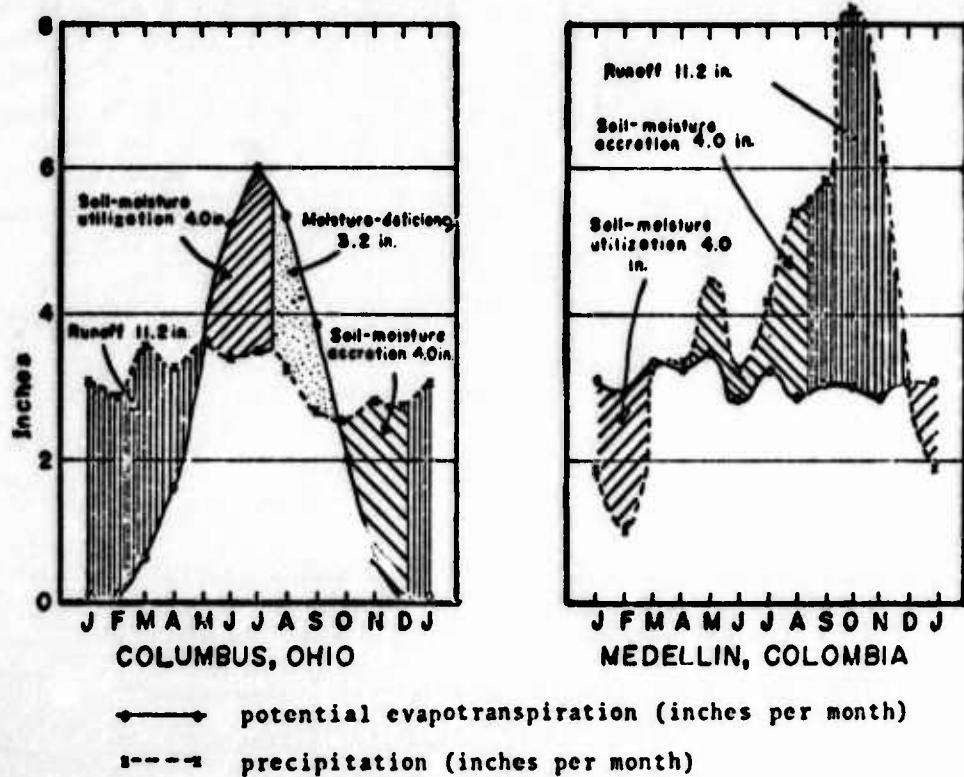
From C. W. THORNTHWAITE, Notes on tropical
climatology, (Paper presented at Caribbean
Soils Conference), San Juan, Puerto Rico,
Apr. 8, 1950 (Mimeo)

Figure 16. Mean monthly rainfall and evapotranspiration
for Columbus, Ohio, and Medellin, Colombia

Comparison of Prediction Factors

7. Other discussions point out the success of the prediction method
using specific measurements to predict moisture contents in temperate and
tropical climates. The tentative average method has been used with limited
success in the temperate climates. However, when the tentative average
method is applied to tropical climates predictions are very poor. Let us
now consider the prediction factors.

Seasons

8. In the temperate climates there are four seasons; winter (wet),
summer (dry), spring (wet to dry), and fall (dry to wet). Because soil

moisture depletes faster in the summer (growing) season, the character of the depletion curve used in the summer differs from that of the other seasons. In the spring and fall seasons the depletion rates are similar, so the same rate is used for both seasons.

9. In the tropical climate there is no distinct change from one season to another. The temperatures are more constant than in the temperate zone and the growing season is continuous. There are wet seasons and dry seasons but the factors influencing depletion (temperature, evapotranspiration, etc.) do not vary with season; thus, the character of the depletion curve does not change. The rate of depletion in the tropical climate closely follows that of the transition seasons in the temperate climate. Therefore, the transition depletion has been used for the entire year in the tropics when the tentative average method is applied. Thailand is an exception in that the wet and dry season depletion rates are different, and in that there is no transition rate between the two seasons.

Rainfall

10. In studies conducted in temperate climates, rainfall varied from 3.7 in. annual rainfall in New Mexico, U. S., to 68.4 in. in Pennsylvania, with long-term annual averages of about 8 in. to about 59 in. These annual averages are much less than the annual averages in the tropics, which in Hawaiian study sites vary from about 19 to about 188 in. Figs. F5 through F8 show some of the extremes in the study areas in the tropics. It will be noted that the differences within each climate zone are as great or greater than between zones. Thus, it appears that temperate and tropical climate areas are not meaningful groupings for comparing rainfall as a prediction factor.

Minimum storm

11. In the temperate climates, 84 percent of 106 sites had a minimum effective storm of 0.10 in. Of 47 sites in the tropics, only 47 percent had a minimum effective storm of 0.10 in. while 42 percent had greater than 0.10-in. minimum storm. Apparently more rain is needed to make a significant change in soil moistures of the tropical soils tested than in those of the temperate soils tested (table F1).

Field maximum and field
minimum moisture contents

12. Since field maximum and field minimum moisture contents are
limits of the soil moisture depletion range it is difficult to separate
them for discussion. Table F2 lists the ranges and averages of the mea-
sured field maximums and field minimums of prediction sites in the tropical
studies. Averages for each tropical study are shown plus the tropical and
temperate averages. The data indicate that the field maximum and field
minimum moisture contents are much higher in the tropical climate than in
the temperate climate. However, it should be recognized that data for the
tropical sites are biased in that the sites were selected primarily in wet,
low-lying areas in accordance with suggestions made by the consultants at
the 1958 conference that tests be conducted in areas that would provide
trafficability problems.

13. Fig. F9 shows, on a horizontal soil moisture scale, the demarca-
tion of the ranges of table F2. It is interesting to note that the average
field maximums and field minimums of Thailand (where probably a more repre-
sentative selection of sites was made) more closely resemble the averages
of the temperate climates than those of any other tropical area.

14. The danger in the use of averages without the qualifying inclu-
sion of extremes is illustrated by the average maximum and minimum moisture
contents for the 6- to 12-in. layer of Hawaii and Puerto Rico. The average
field maximum and the average field minimum for soils of Hawaii are 3.00
in. and 2.32 in. (0.68-in. range). For Puerto Rico they are 2.92 in. and
2.12 in. (0.80-in. range). Yet, the limits of the extreme values are 3.75
in. and 1.76 in. (1.99-in. range) for Hawaii and 3.73 in. and 0.47 in.
(3.26-in. range) for Puerto Rico.

15. Table F3 shows the mean deviations of measured field maximum and
minimum moisture contents from those computed by the tentative average
equations developed for soils of the temperate climates. These high devia-
tions indicate that the equations are not adequate for estimating the field
maximum and minimum moisture contents for soils of the tropics.

Accretion relations

16. Average accretion regressions for class I and class II

F7

accretions were developed from specific relations for each of the countries in tropical climates. These are compared with the tentative average accretion regressions for the temperate climate in figs. F10 and F11 for class I and class II accretions, respectively. The data indicate that soils in tropical climates tend to have slightly higher rates of accretion than those in temperate climates for the same amount of rainfall or available storage.

Depletion relations

17. Specific depletion relations for the 0- to 6-in. and 6- to 12-in. layers were developed at each site from a family of depletion curves. This family of curves was taken from the daily soil moisture record.

18. Fig. F12 shows the average depletion curves for Puerto Rico clay soils and the transition season average depletion curves for temperate clay soils. The Puerto Rico curves are averages of the specific depletions for all the Puerto Rico prediction development sites.

19. Figs. F13 through F16 show specific depletion relations for soils in other tropical countries. Because of the wide divergence in the curves, it was decided not to use an average depletion curve for these countries.

20. In all tropical studies except Thailand there was no change in the depletion relations of each soil layer per site for the entire year; one curve was adequate to describe depletion. In Thailand there were two distinct depletion relations for each soil layer per site as noted in fig. F17.

Moisture Prediction in the Tropics

21. Moisture predictions using specific accretion and depletion relations and measured field maximums and minimums can be made in the tropics with accuracies similar to those for temperate areas. Average deviations between measured and predicted moisture contents for soils of each tropical country are:

	Average Absolute Deviation	
	0- to 6-in. Layer	6- to 12-in. Layer
Puerto Rico (study 1, adjusted for water table conditions)	0.09	0.07
Puerto Rico (study 2, critical water table periods omitted from prediction)	0.16	0.13
Costa Rica (soil moisture by gravimetric measurements)	0.19	0.17
Thailand (well-drained sites only)	0.14	0.10
Colombia (soil moisture by gravimetric measurements)	0.32	0.27
Panama (study 2)	0.12	0.08

The average absolute deviations for soils in temperate climates are 0.08 and 0.06 in. for 0- to 6-in. and 6- to 12-in. layers, respectively.

22. In the second Puerto Rico study, in addition to specific predictions, predictions were made using:

    a. Average field maximum and minimum moisture contents, average accretion relations, and average depletion relations for Puerto Rico.

    b. Specific field maximum and minimum moisture contents, average accretion relations, and average depletion relations for Puerto Rico.

Deviations between measured and predicted moisture contents derived from methods a and b are:

Puerto Rican Average Method

		Average Absolute Deviations			
		Method a Puerto Rican Average Field Maximum and Minimum Soil Layer		Method b Specific Field Maximum and Minimum Soil Layer	
Soil	No. of Sites	0- to 6-in.	6- to 12-in.	0- to 6-in.	6- to 12-in.
Group I*	10	0.35	0.30	0.19	0.16
Group II**	6	0.60	0.61	0.43	0.30
Group III†	5			0.39	0.33
Average	21			0.30	0.24

  * Group I: prediction development sites with specific factors.
 ** Group II: satellite sites.
  † Group III: prediction development sites without specific factors developed by the usual procedure.

23. The second study in Puerto Rico was conducted by Mr. Tom Hicks. He draws the following conclusion (in unpublished draft report):

> On the whole, the average deviations obtained when using average field-maximum and minimum moisture contents do not constitute a sufficient degree of accuracy. However, the average deviations, 0.30 in. in the 0- to 6-in. layer and 0.24 in. in the 6- to 12-in. layer, obtained when using specific field-maximum and minimum moisture contents for a given site, indicate that a reasonable degree of accuracy may be obtained when average Puerto Rico depletion curves and accretion regressions determined through intensive sampling at a few sites are applied to Puerto Rico sites at which only sporadic data have been obtained.
>
> ... it is concluded that Puerto Rico average field-maximum and minimum moisture contents determined from grouping sites on the basis of soil texture (sand, silt, and clay), are inadequate for moisture prediction purposes and that field-maximum and minimum values for individual sites, determined by measurement or prediction, must be used if moisture is to be predicted with any reasonable degree of accuracy....

24. The tentative average method of the temperate climate was applied to the Puerto Rico data with the following results.

Temperate Tentative Average Method

Soil	No. of Sites	Average Absolute Deviations			
		Estimated Field Maximum and Minimum		Specific Field Maximum and Minimum	
		Soil Layer		Soil Layer	
		0- to 6-in.	6- to 12-in.	0- to 6-in.	6- to 12-in.
Group I	11	0.59	0.56	0.19	0.16
Group II	6	0.76	0.79	0.37	0.35
Group III	5			0.40	0.29
Average	22			0.29	0.29

In his draft report, Mr. Hicks concluded that:

> As shown in table ___, the average absolute deviations obtained by using approximate field-maximum and minimum moisture contents are extremely high. The algebraic deviations for most sites are negative and unusually high, indicating that the predicted moisture contents generally run very low, and for some sites, never approach the measured moisture contents. Since figs. __ and __ show good agreement for U. S. and Puerto Rico average accretion regressions and average depletion curves, respectively, it can reasonably be

F10

assumed that the inaccurate and highly negative
deviations occurring in this analysis are largely
attributable to the apparent difference in approximate
and specific field-maximum and minimum moisture contents,
especially the minimum values....

25. For subsequent studies in the tropics, specific factors were
used.

Conclusions

26. The temperate and tropical climate areas of the earth, while
grossly distinct in character, have as great or greater variation in climate
within each zone as between zones.

27. Soil moisture prediction factors in the two climate zones differ
as follows: (a) Generally, average annual rainfall is greater in tropical
climates than in temperate climates. (b) The tropical soils appear to
require more rainfall than temperate soils before effective wetting occurs.
(c) Tropical soils appear to be generally wetter, having higher minimum
moisture contents. (d) The equations for estimating field maximum and
minimum moisture contents for temperate soils are not adequate for soils
of the tropics. (e) With the exception of Thailand, the depletion rate per
soil layer per site does not change with seasons as it does in temperate
climates.

28. Soil moisture prediction with specific data seems adequate for
both temperate and tropical climates. The tentative average method for
soil moisture prediction is not applicable to tropical soils. The predic-
tion system cannot provide true predictions until ways are found to (a)
accurately estimate field maximum and field minimum moisture contents,
(b) establish accretion and depletion relations by some method other than
taking daily records in place at the site, and (c) eventually use weather
forecasts rather than weather records.
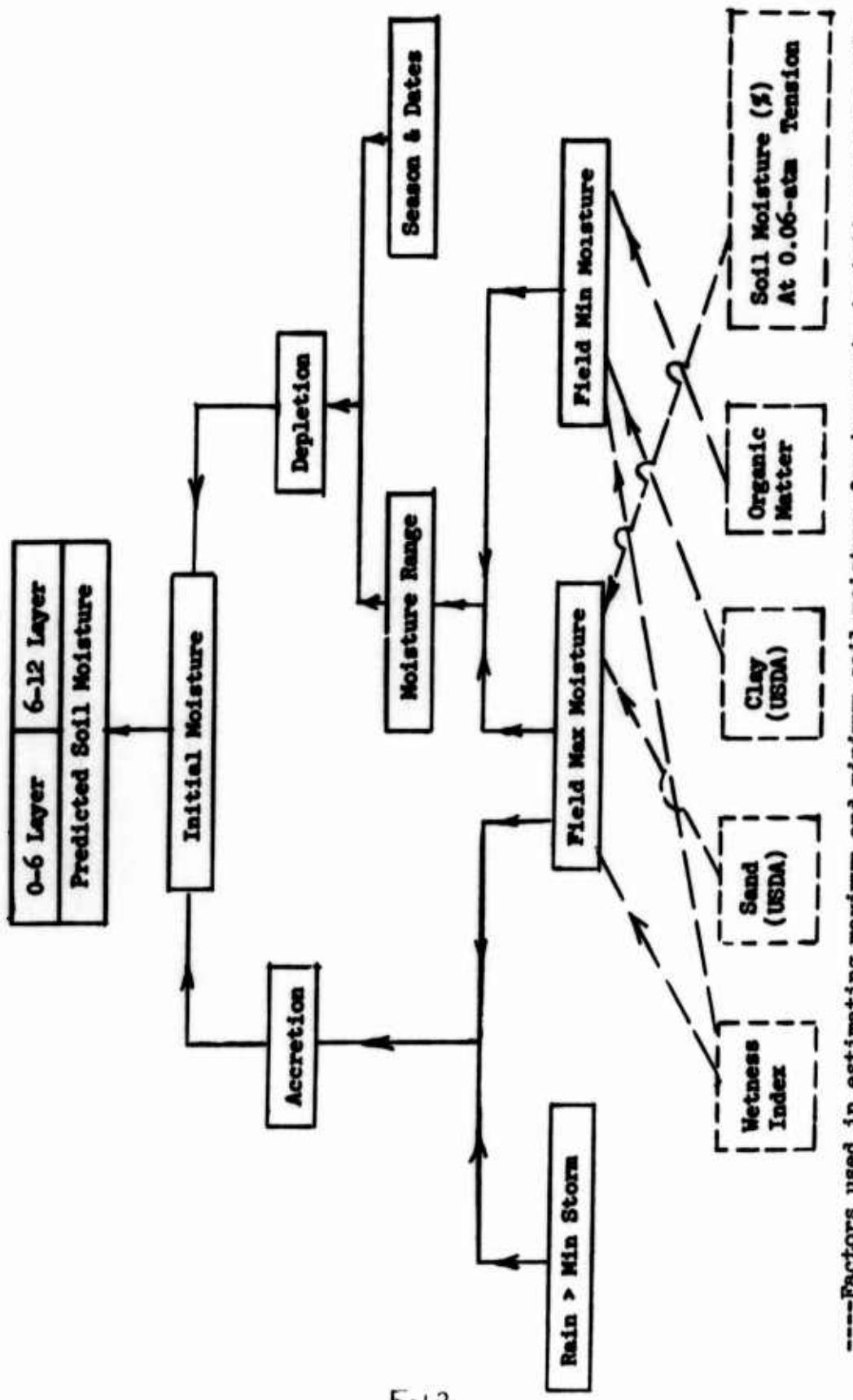
Fig. Fl. Soil moisture prediction factors

----Factors used in estimating maximum and minimum soil moisture for temperate tentative average only
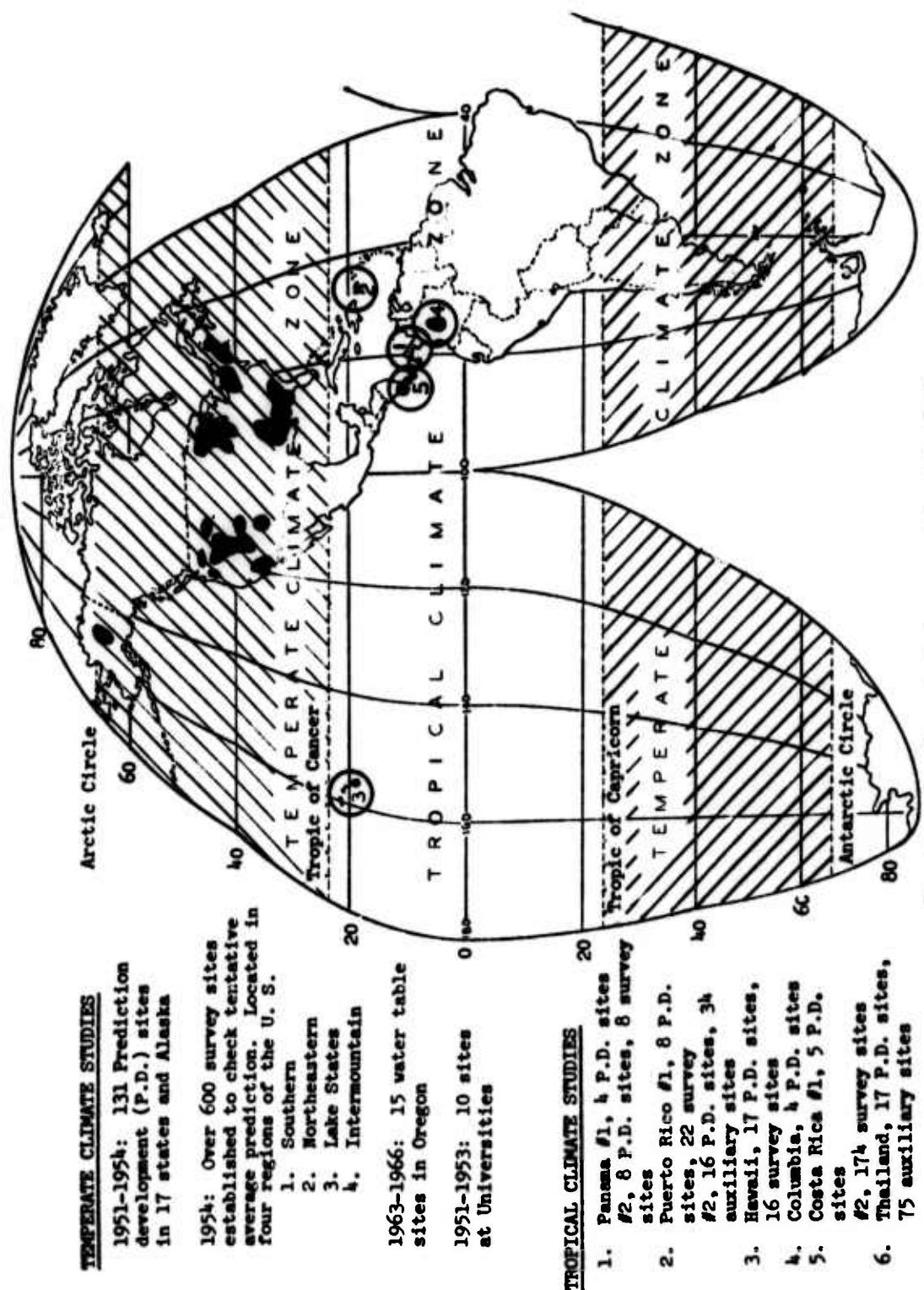
Fig. F2. Location of study areas (sheet 1 of 2)

TEMPERATE CLIMATE STUDIES

1951-1954: 131 Prediction development (P.D.) sites in 17 states and Alaska

1954: Over 600 survey sites established to check tentative average prediction. Located in four regions of the U. S.
1. Southern
2. Northeastern
3. Lake States
4. Intermountain

1963-1966: 15 water table sites in Oregon

1951-1953: 10 sites at Universities

TROPICAL CLIMATE STUDIES

1. Panama #1, 4 P.D. sites #2, 8 P.D. sites, 8 survey sites
2. Puerto Rico #1, 8 P.D. sites, 22 survey #2, 16 P.D. sites, 34 auxiliary sites
3. Hawaii, 17 P.D. sites, 16 survey sites
4. Columbia, 4 P.D. sites
5. Costa Rica #1, 5 P.D. sites
6. Thailand, 17 P.D. sites, #2, 174 survey sites 75 auxiliary sites

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Fig. F2 (sheet 2 of 2)

Fig. F3. Average annual temperature (from Encyclopedia Britannica World Atlas) (sheet 1 of 2)

Fig. F3 (sheet 2 of 2)

F-16
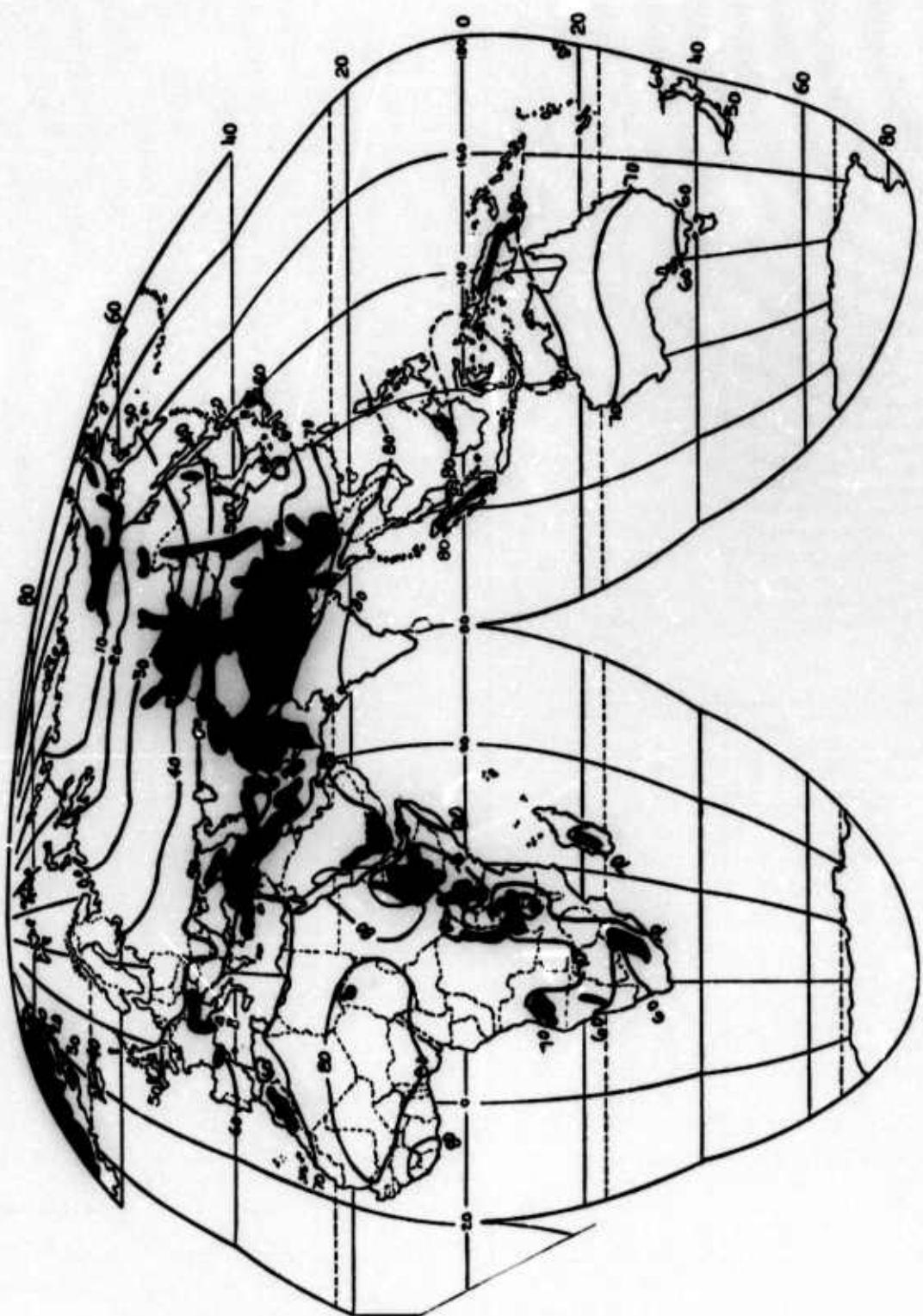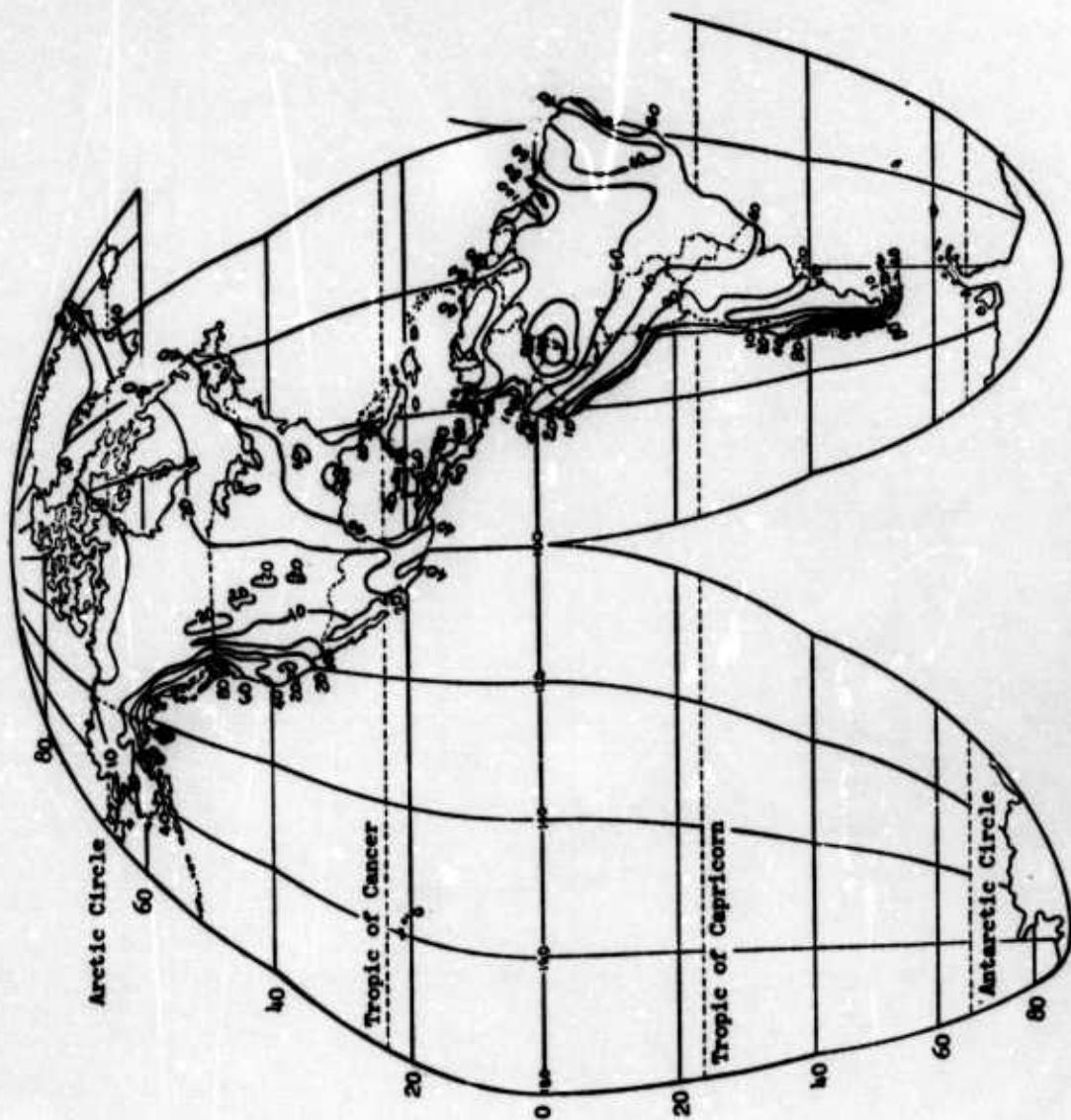
Fig. F4. Average annual rainfall (from Encyclopedia Britannica World Atlas) (sheet 1 of 2)

Fig. F4 (sheet 2 of 2)

F-13
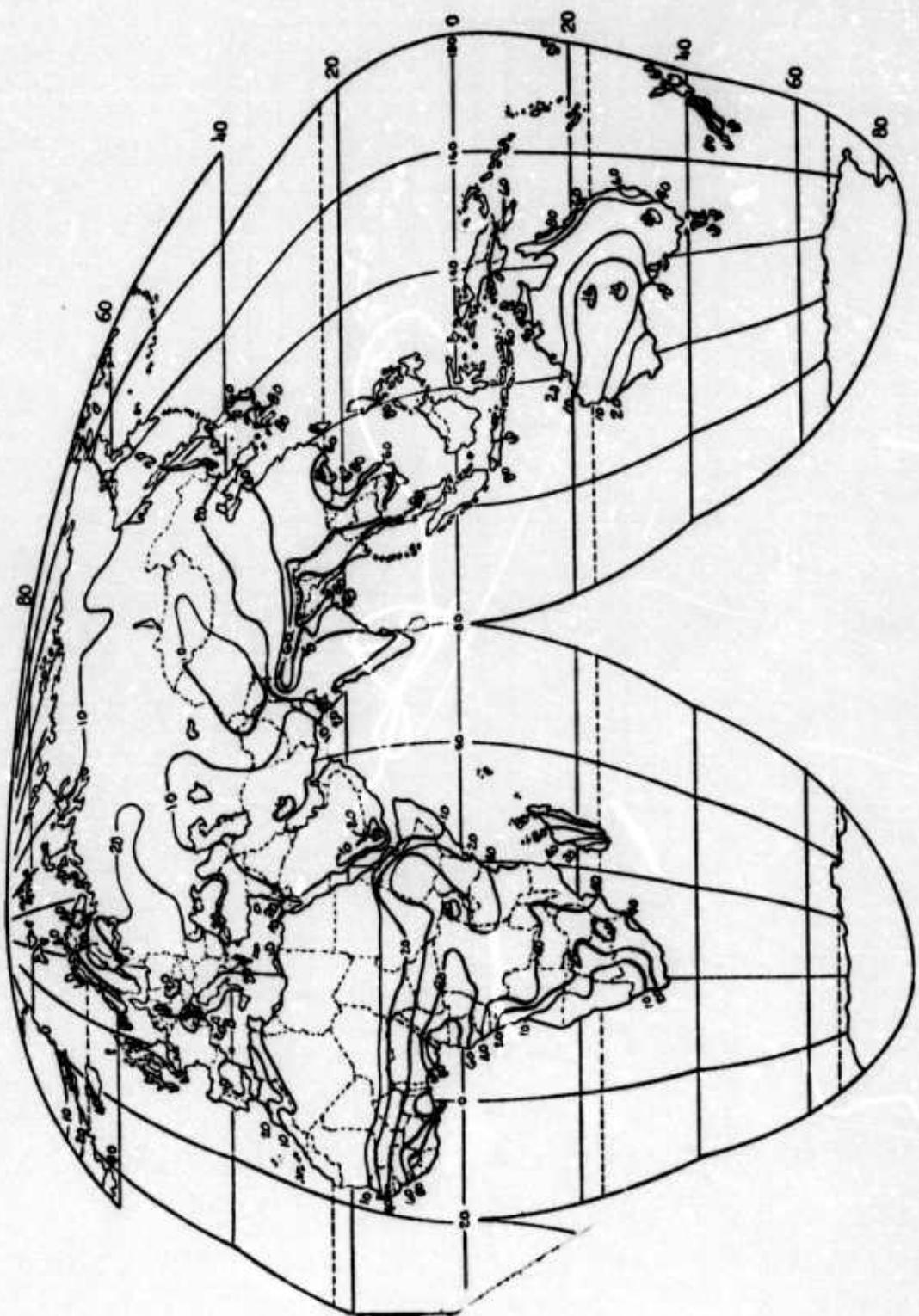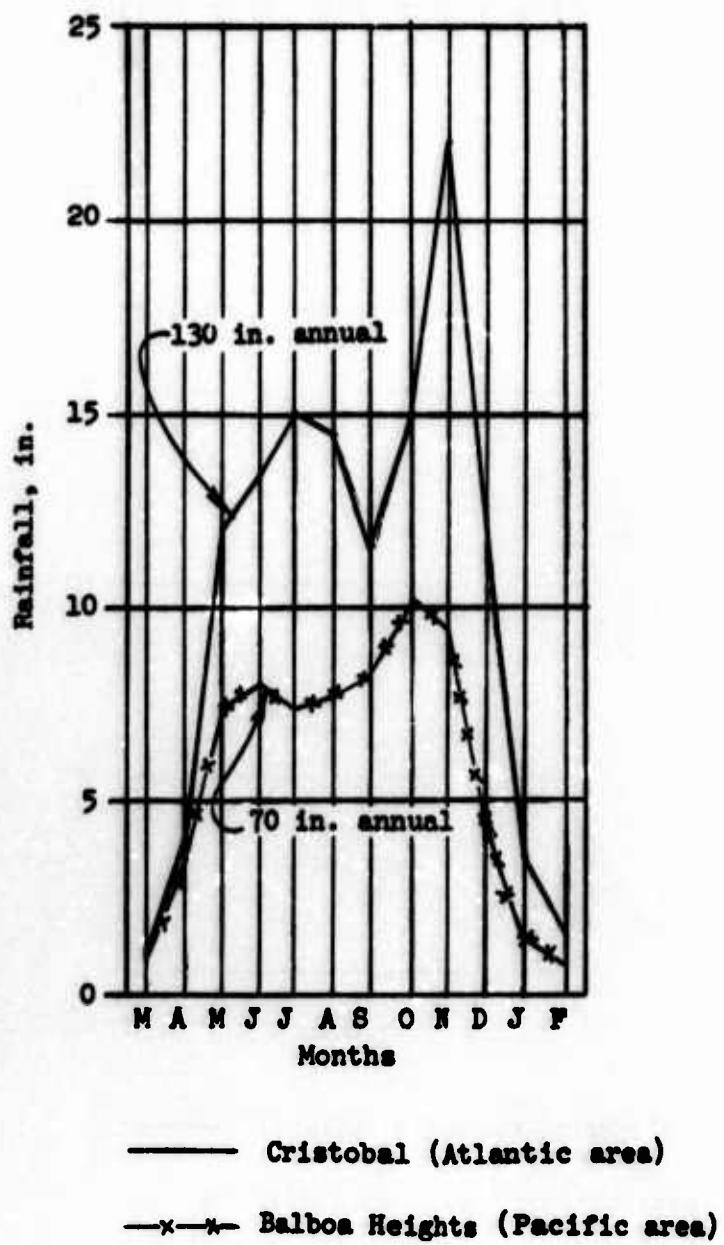
Fig. F5. Mean rainfall in two areas of Panama Canal Zone (Study 2)
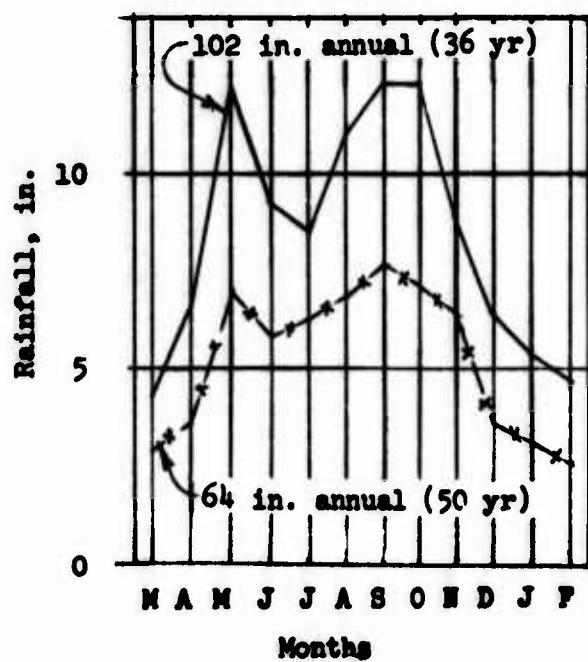
Fig. F6.   Mean rainfall in Puerto Rico
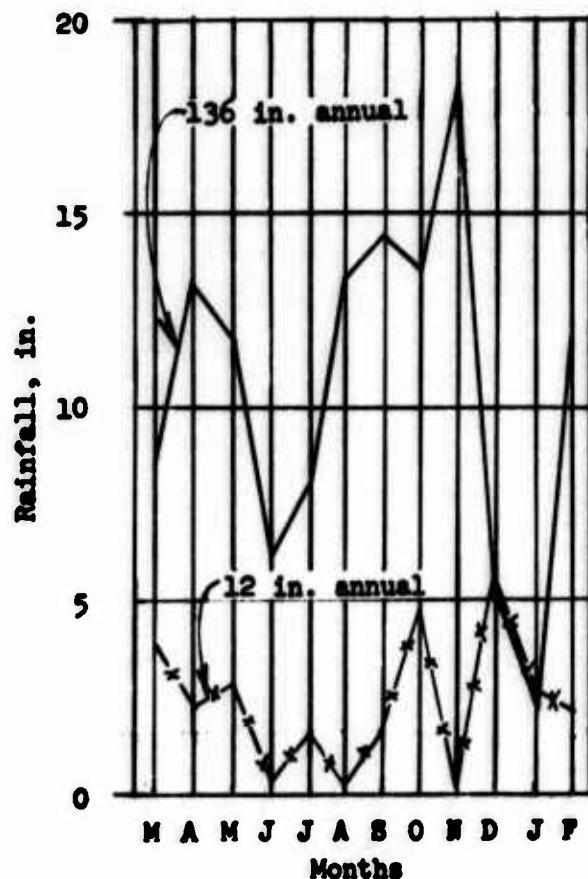
Fig. F7.   Rainfall for sites 14 and 6 in
           Hawaii, year of study

F-20
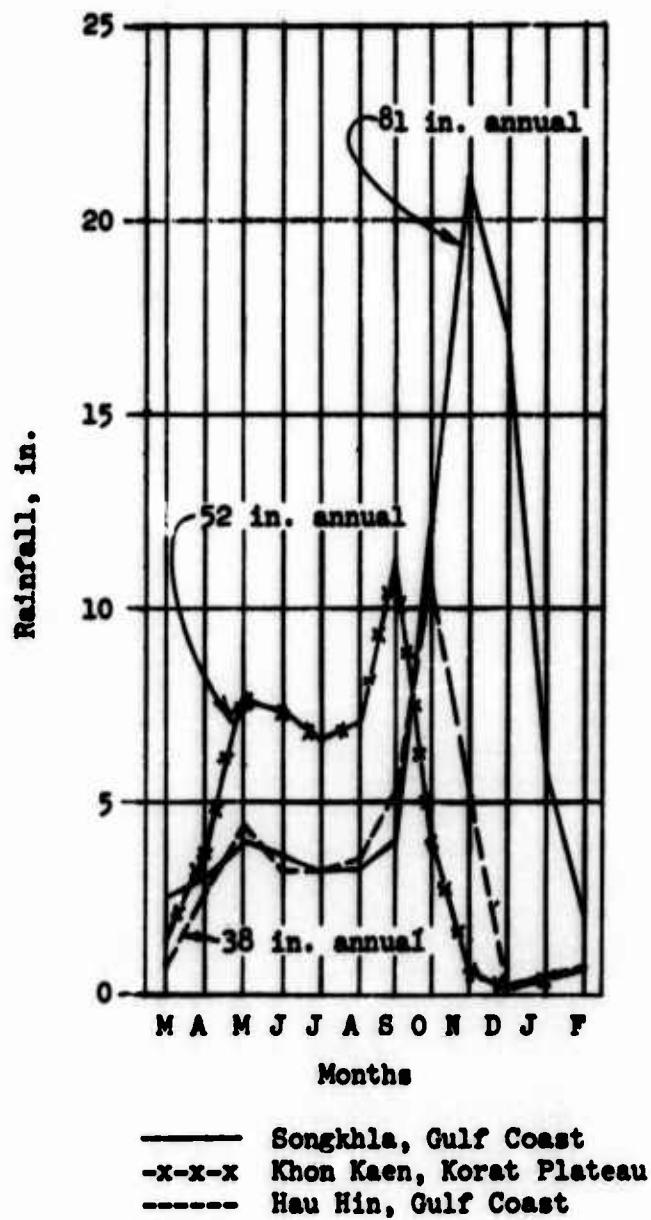
Fig. F8. Rainfall in three study areas of Thailand,
period of study
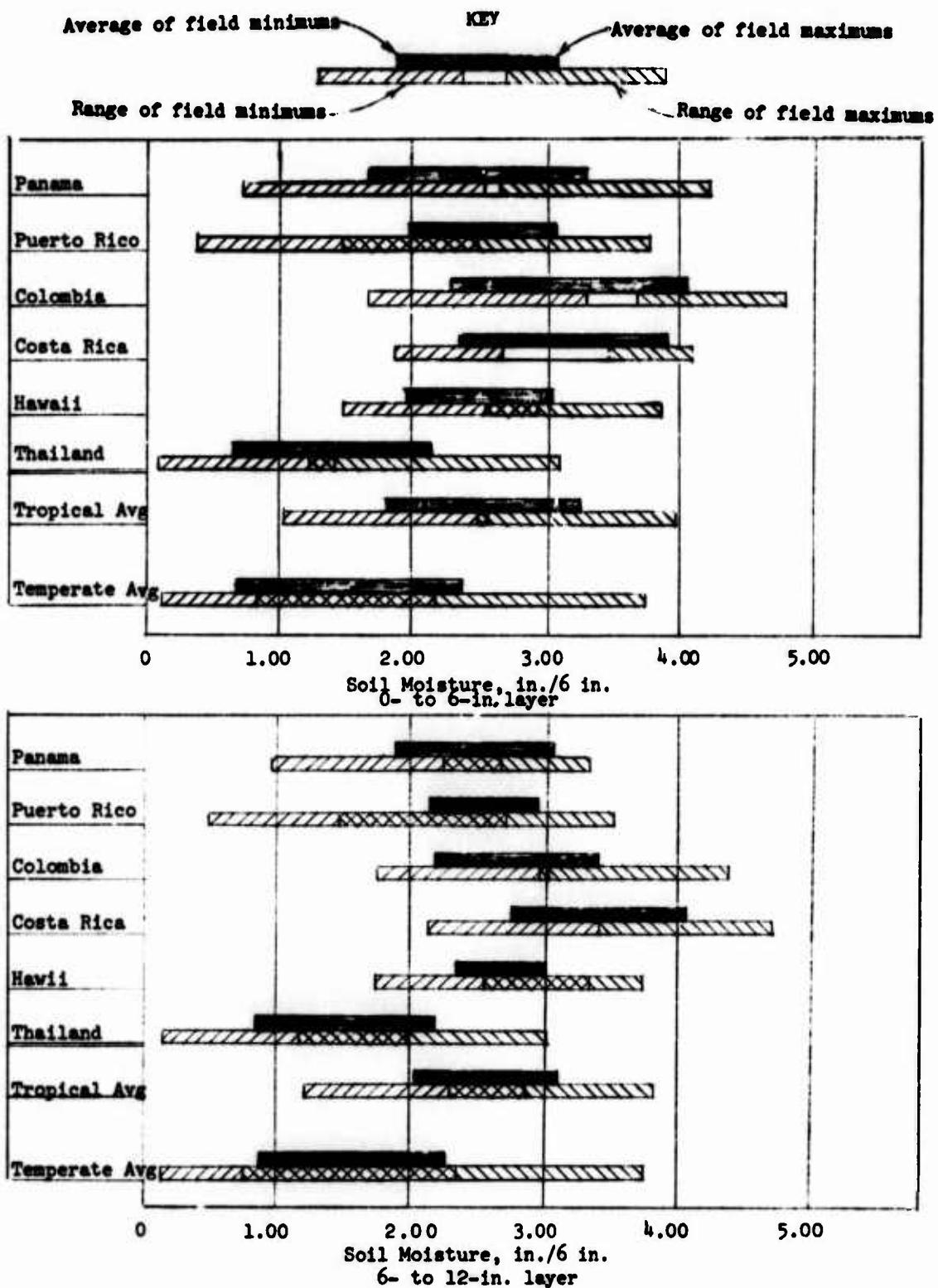
Fig. F9. Measured field maximum and minimum moisture ranges
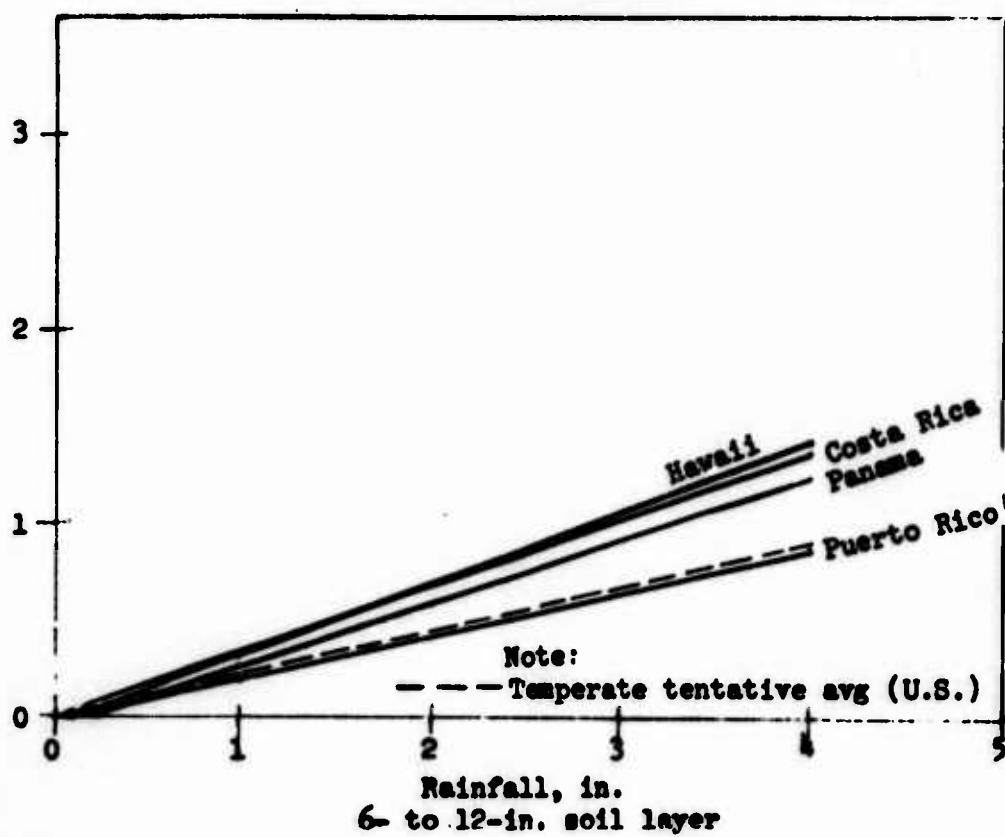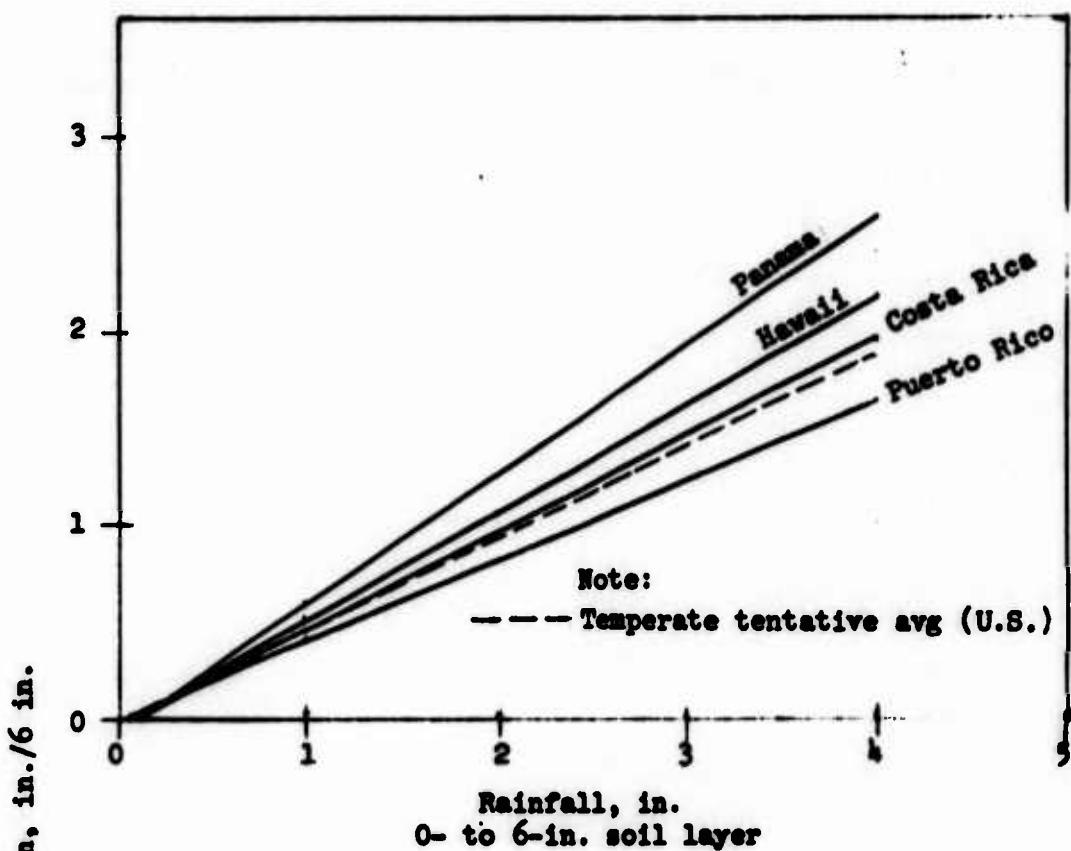
Fig. F10. Average regressions for class I accretions
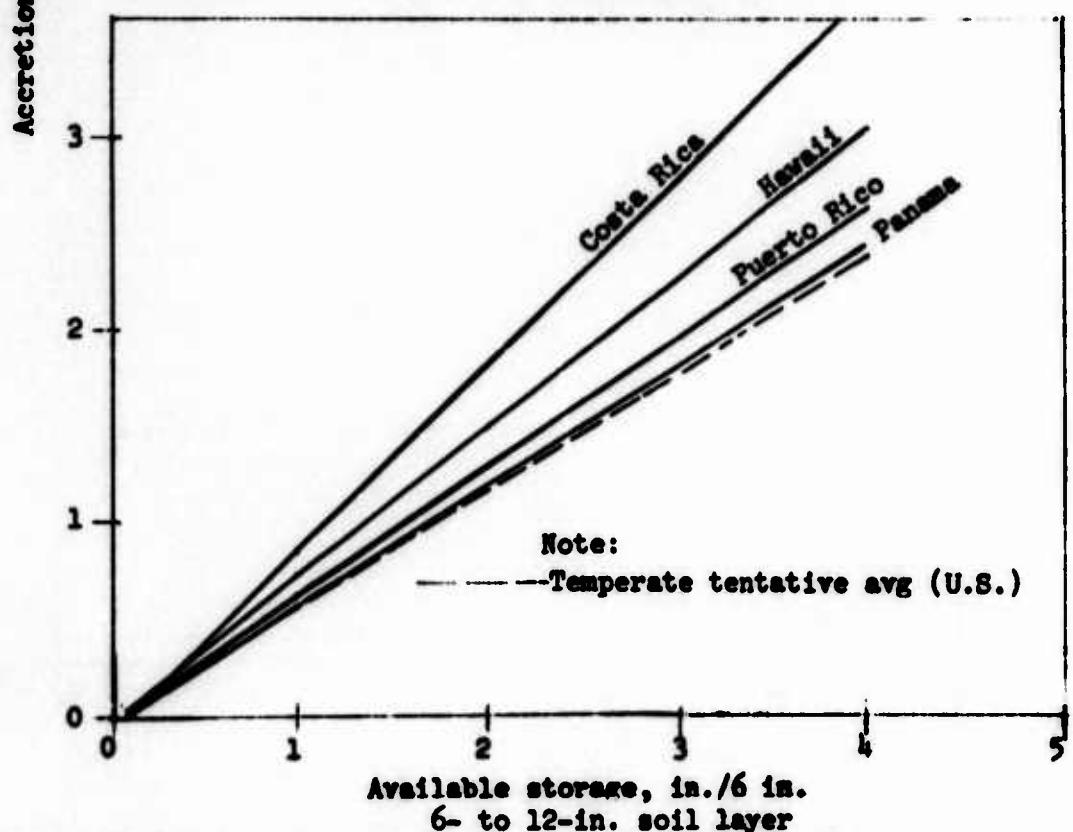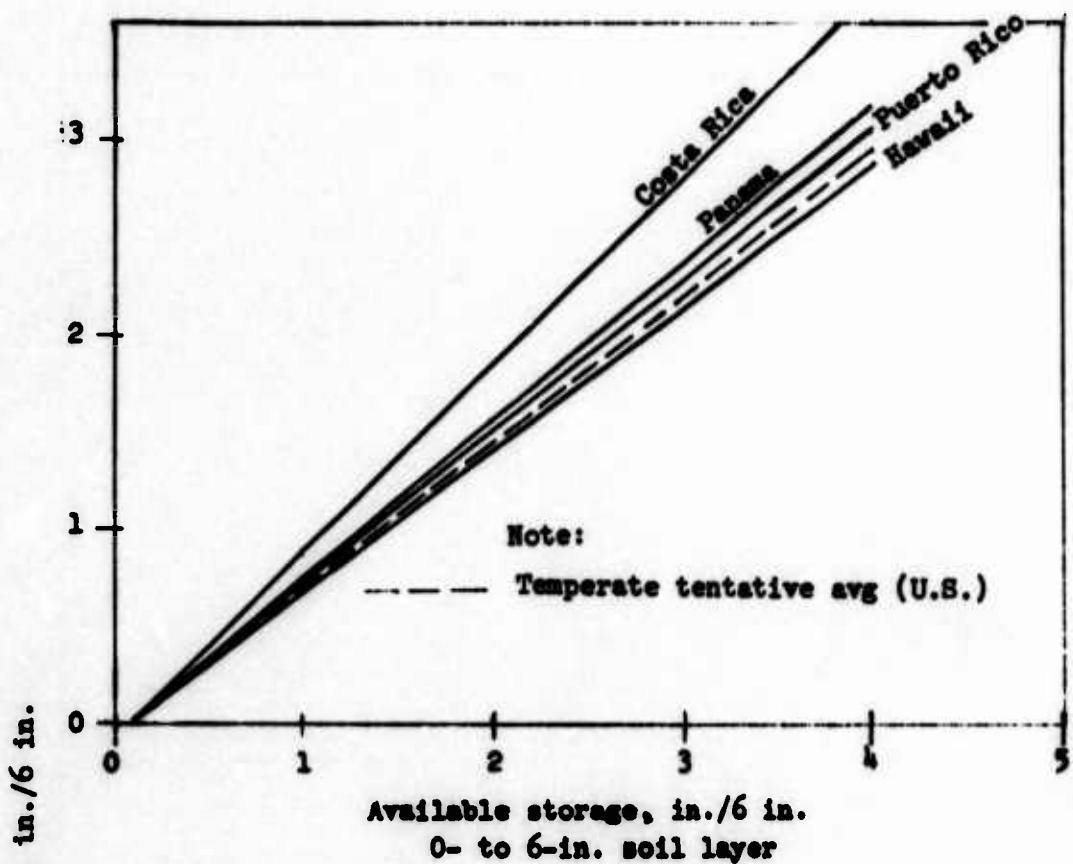
Fig. F11. Average regressions for class II accretions
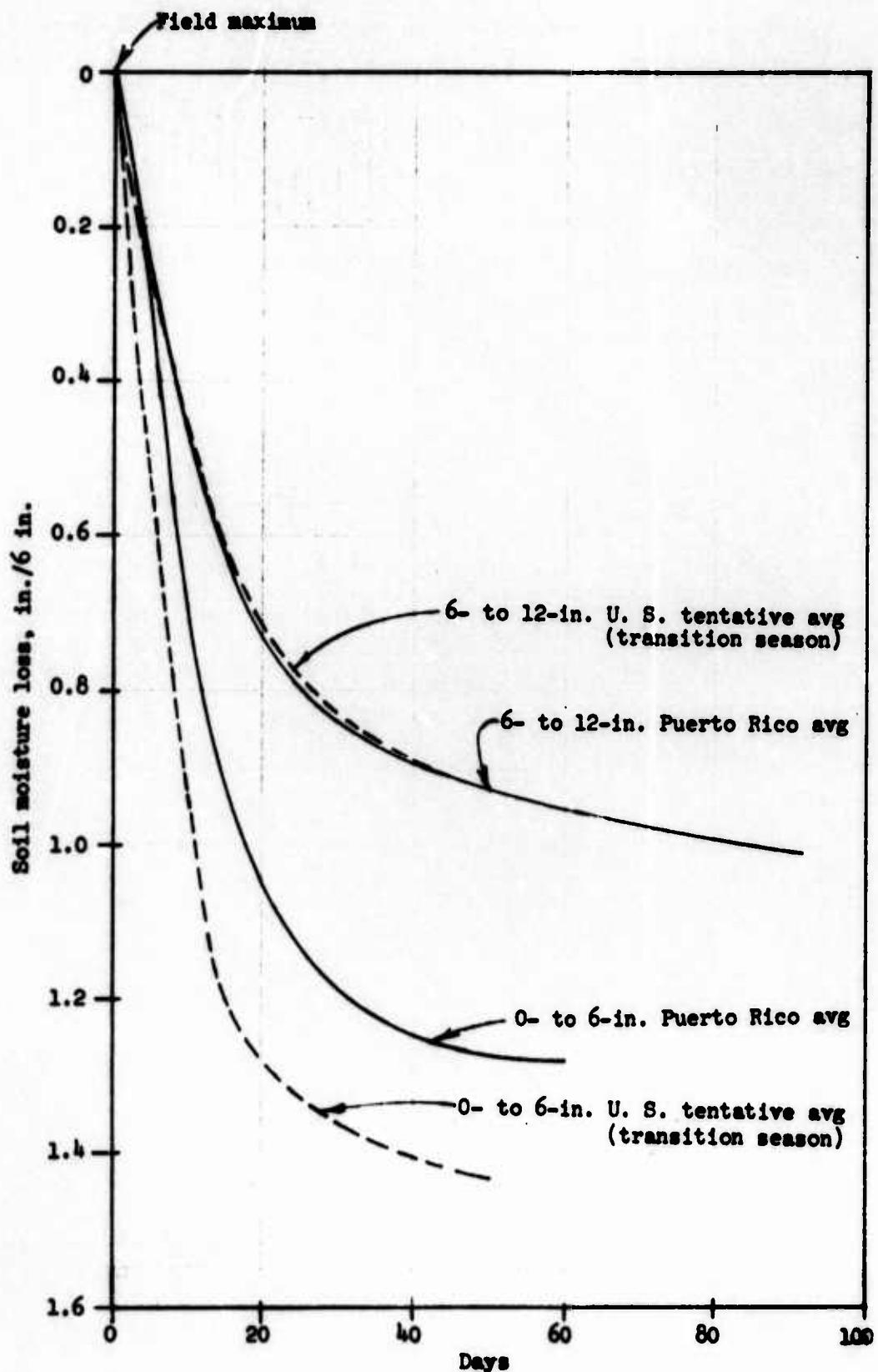
Fig. F12. Average moisture loss from field maximum, clay textural group, Puerto Rico

F-25
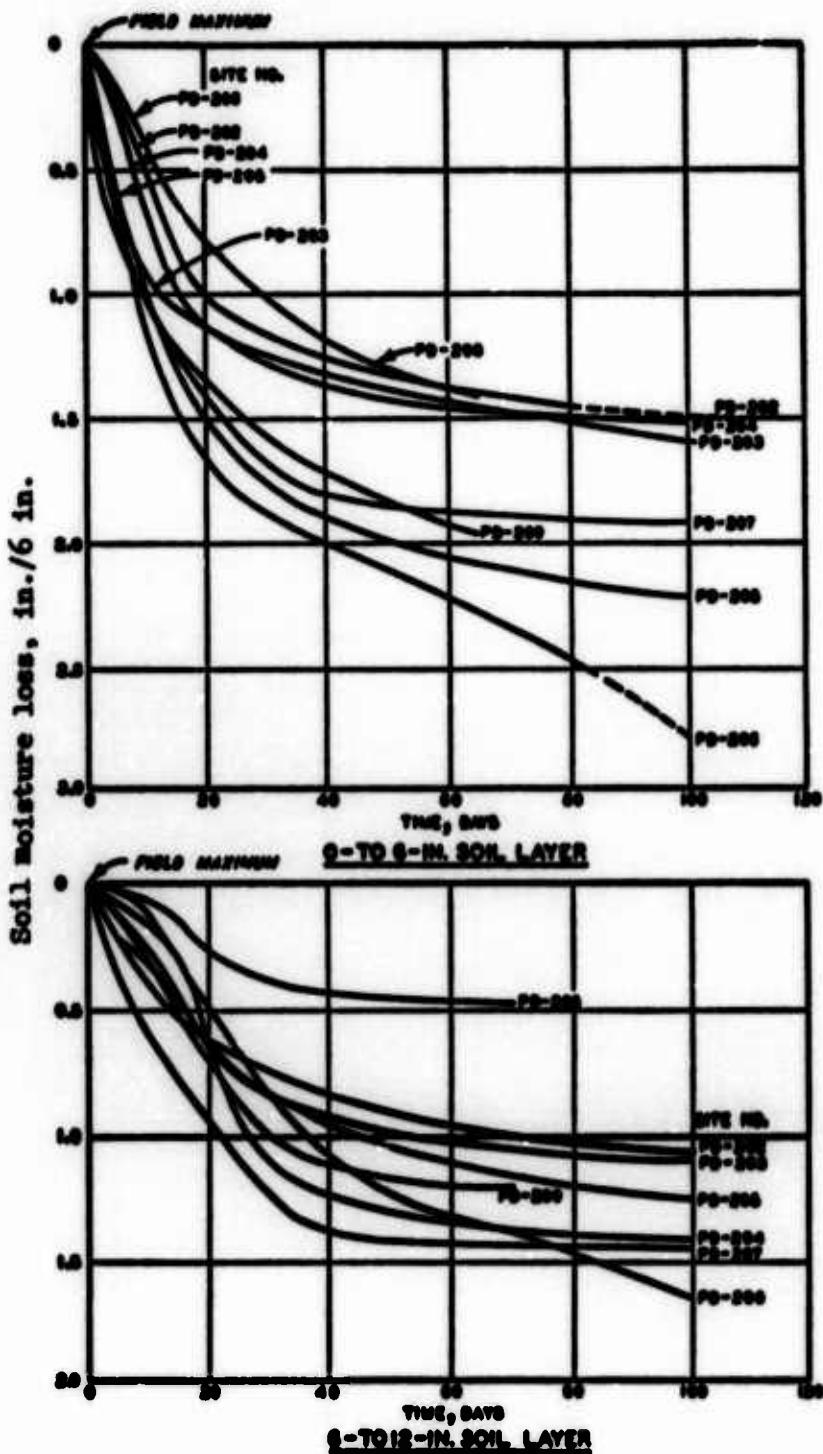
Fig. F13. Depletion curves for sites in Panama

F 26
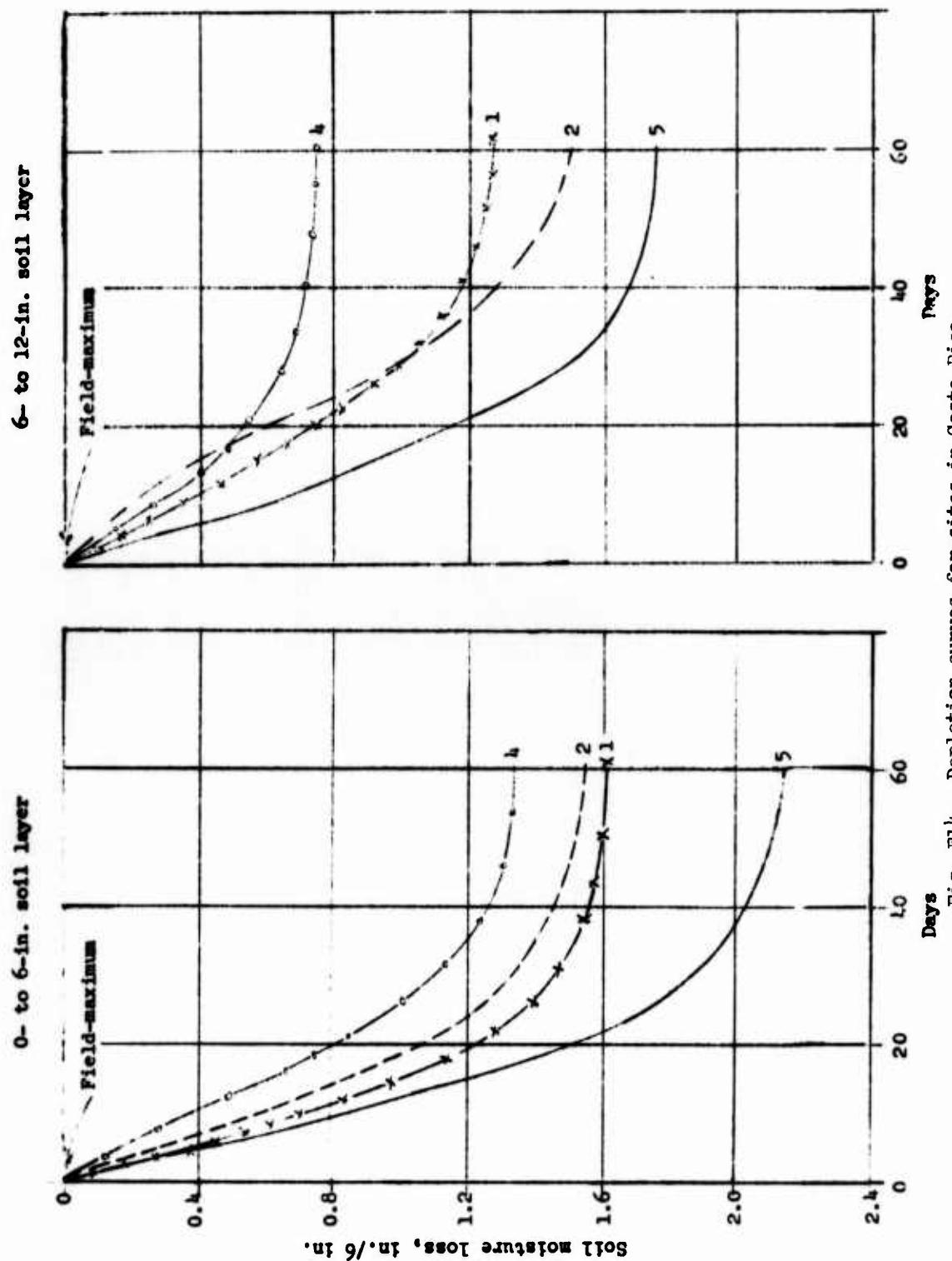
Fig. F14. Depletion curves for sites in Costa Rica
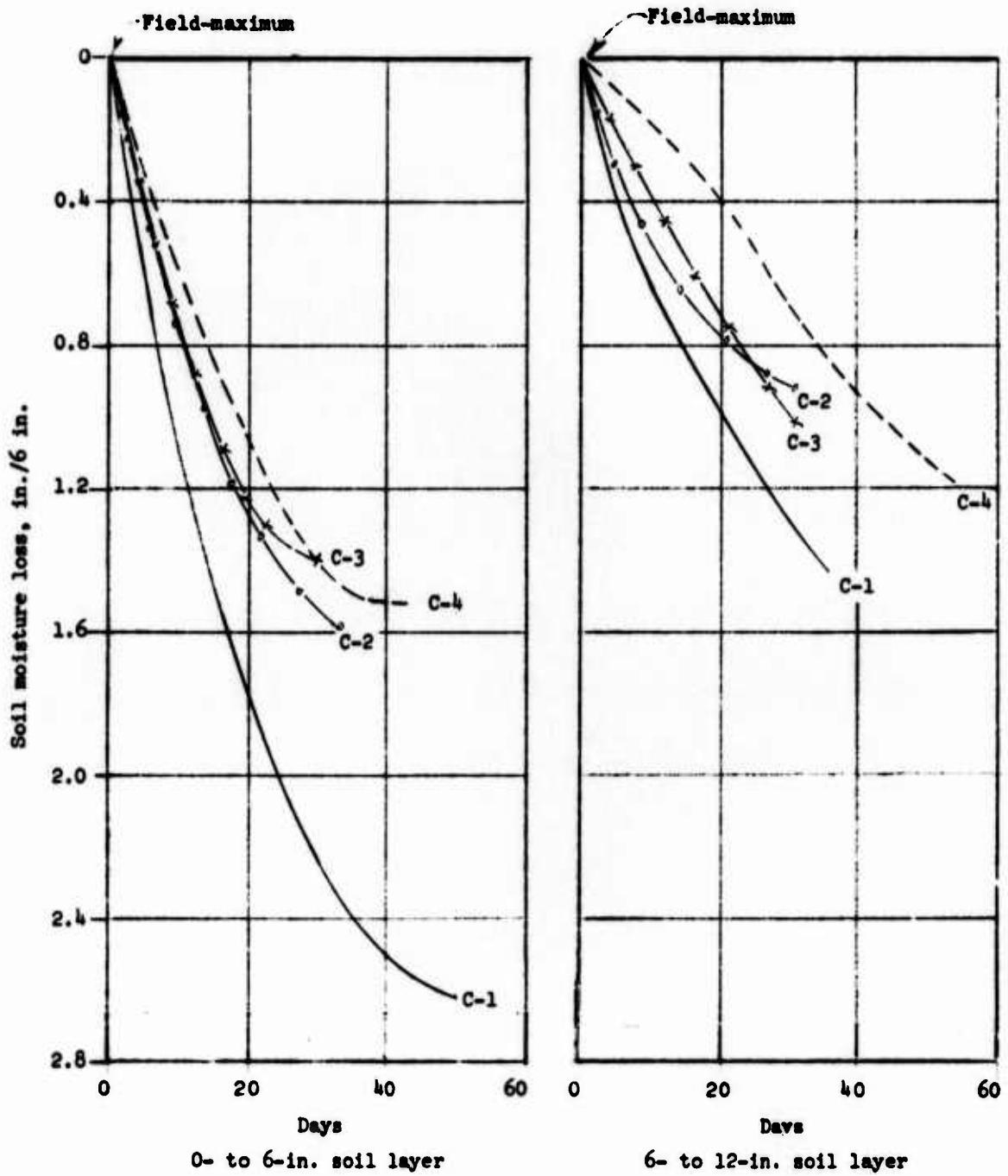
Fig. F15.   Depletion curves for sites in Colombia
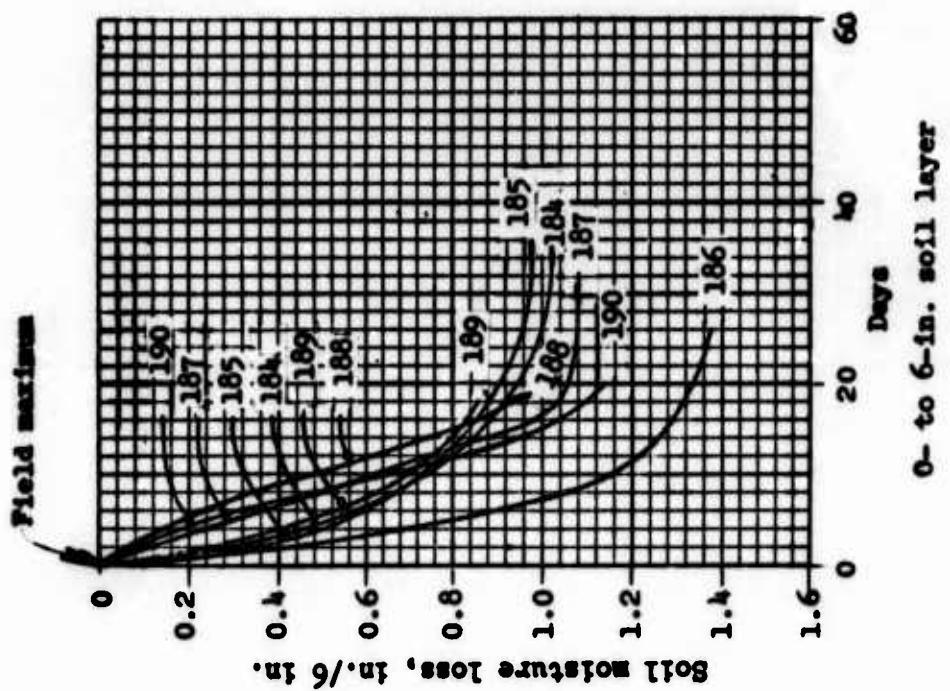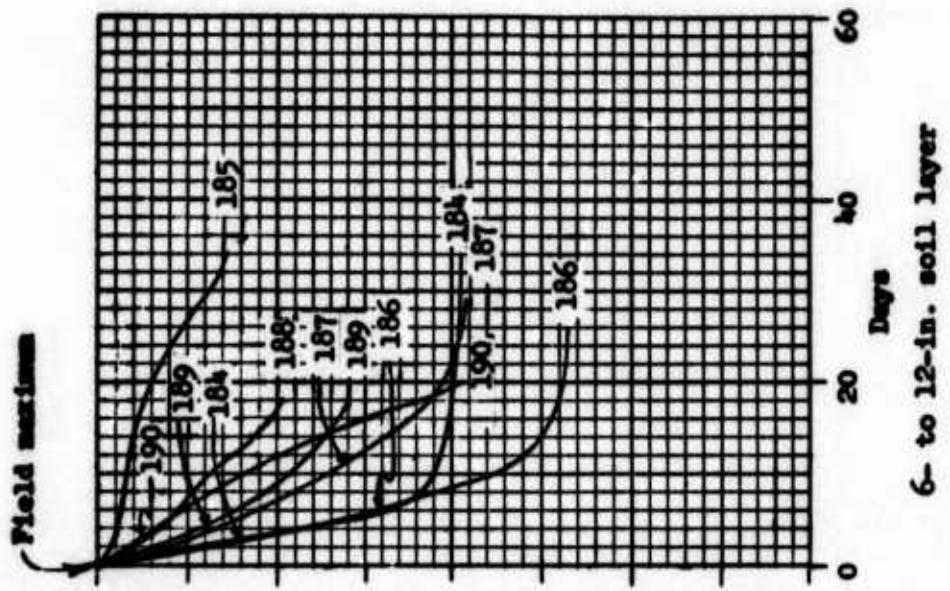
Fig. F16. Depletion curves for sites in Hawaii
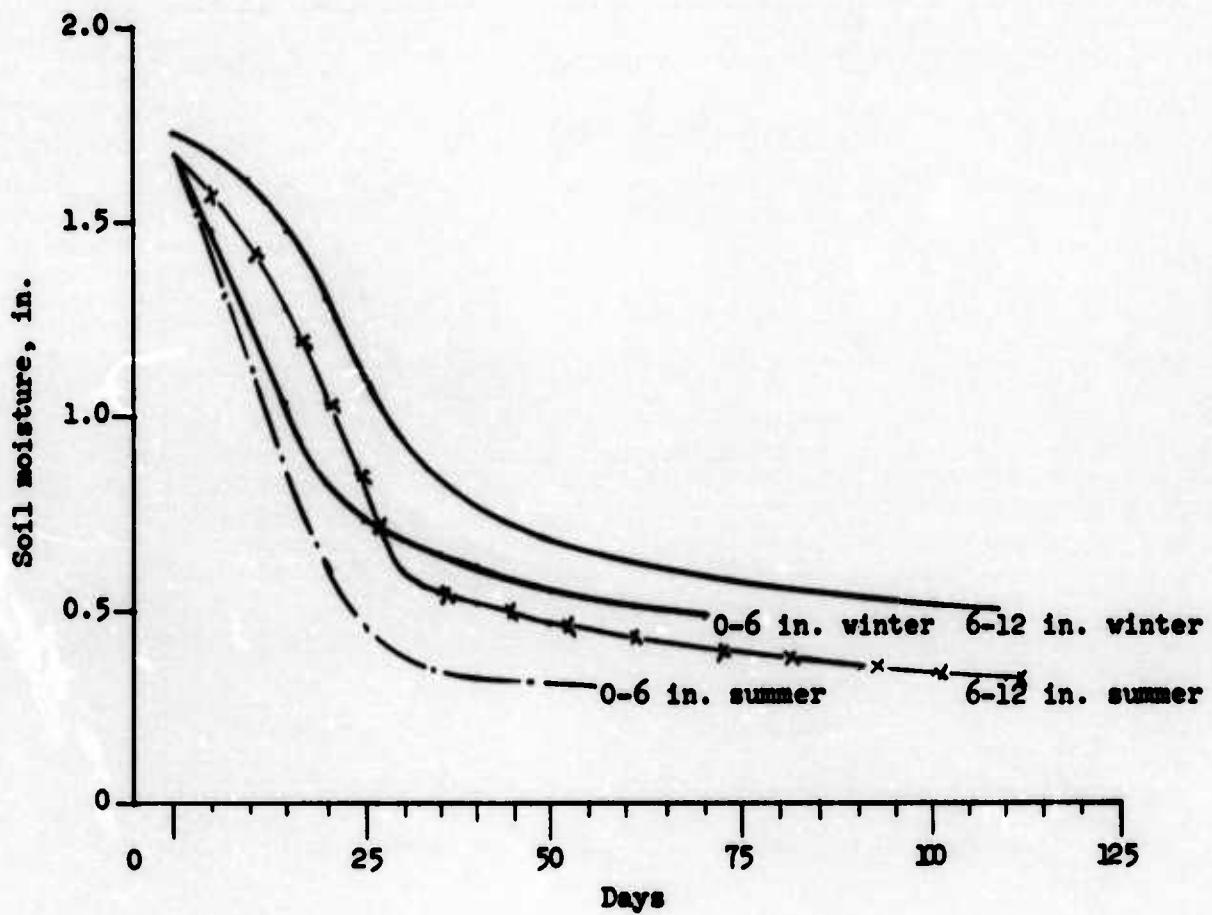
Fig. F17. Soil moisture depletion, in. per 6 in. of soil; Thailand
site 247

F. 30

Table F1

Minimum Storms

Min Effective Storm	No. of Sites	% of Total
Tropical Sites (47)		
<0.10	5	11
0.10	22	47
0.15	17	36
0.20	17	36
Temperate Sites (106)		
0.05	5	5
0.10	89	84
0.15	2	2
≥0.20	10	9

Table F2

Measured Field Maximum and Field Minimum Moisture Contents,

Prediction Development Sites

Study	Soil Layer in.	No. of Sites	Moisture, in. per 6 in. of Soil				Range
			Avg Maximum	Range of Maximums	Avg Minimum	Range of Minimums	Avg Max-Avg Min
Tropical							
Panama	0 to 6	12	3.30	2.62-4.21	1.66	0.76-2.55	1.64
	6 to 12	12	3.04	2.22-3.33	1.90	0.98-2.65	1.14
Puerto Rico	0 to 6	19	3.04	1.45-3.79	1.98	0.39-2.45	1.06
	6 to 12	19	2.92	1.45-3.73	2.12	0.47-2.70	0.80
Colombia	0 to 6	4	4.04	3.58-4.80	2.28	1.64-3.30	1.76
	6 to 12	4	3.41	2.95-4.38	2.19	1.77-3.02	1.22
Costa Rica	0 to 6	5	3.90	3.47-4.10	2.32	1.86-2.64	1.58
	6 to 12	5	4.05	3.42-4.74	2.73	2.14-3.42	1.32
Hawaii	0 to 6	7	3.02	2.53-3.86	1.96	1.45-2.92	1.06
	6 to 12	7	3.00	2.54-3.75	2.32	1.76-3.34	0.68
Thailand	0 to 6	17	2.15	1.22-3.09	0.66	0.07-1.41	1.49
	6 to 12	17	2.09	1.18-3.01	0.85	0.14-1.99	1.24
Average	0 to 6	64	3.24	2.48-3.98	1.81	1.03-2.55	1.43
	6 to 12	64	3.09	2.29-3.82	2.02	1.21-2.85	1.07
Temperate							
Average	0 to 6	118	2.37	0.84-3.76	0.70	0.11-2.18	1.67
	6 to 12	118	2.25	0.77-3.78	0.88	0.13-2.34	1.37

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Table F3

Maximum and Minimum Moisture Contents, Mean Deviations

	Deviations (measured from estimated)	
	0-6 in. Layer	6-12 in. Layer
Puerto Rico		
Absolute mean maximum	0.18	0.25
Absolute mean minimum	0.90	0.68
Range, maximum to minimum	0.76	0.47
Colombia		
Absolute mean maximum	1.77	1.33
Absolute mean minimum	0.86	0.74
Range, maximum to minimum	0.91	0.59
Panama		
Absolute mean maximum	0.32	0.31
Absolute mean minimum	0.55	0.67
Range, maximum to minimum	0.46	0.36
Costa Rica		
Absolute mean maximum	0.30	0.79
Absolute mean minimum	0.86	1.15
Range, maximum to minimum	0.65	0.42
Hawaii		
Absolute mean maximum	0.37	0.41
Absolute mean minimum	1.03	1.00
Range, maximum to minimum	0.75	0.62

APPENDIX G: PREDICTING AND PORTRAYING SOIL MOISTURE ON AN
AREAL BASIS IN COSTA RICA

by

A. R. McDaniel

Contents

APPENDIX G: PREDICTING AND PORTRAYING SOIL MOISTURE ON AN
AREAL BASIN IN COSTA RICA

Introduction

1. The amount of moisture in a soil is usually a very good indicator
of the relative strength of that soil. Thus, if the moisture content in
the top few feet of soil can be predicted, then an estimate can be made of
the trafficability of that soil, provided also that the soil type is known.
Several systems exist for predicting soil moisture content (Thornthwaite,
Penman, Blaney and Criddle, and various modifications of these); however,
they are for the most part very general in nature. For example, they
largely ignore differences in soil types and differences in moisture con-
tent values at different depths in a soil, and consider soil moisture con-
tent in a thick layer (usually the root zone) as an entity, and on monthly
or seasonal bases only. Such systems may be useful for strategic-type
planning, but they are not suitable for predicting changes for tactical
situations. Only the WES system appears promising, because of its detail,
as a basis for the prediction of moisture content changes on a day-to-day
basis as required for military purposes. This paper describes a system
for predicting and portraying soil moisture content on an areal basis, be-
lieved to be potentially useful to the military. Data for Costa Rica were
used in the development of the system because these data constitute the
most prolific source. They were collected by indigenous personnel under
contract to WES at more than 100 stations over a period of 18 months. It
is emphasized that the system to be described is preliminary in nature. An
attempt is being made to expand the system to include soil strength, but
this work has not progressed far enough to justify presentation at this
time.

System for Prediction and Portrayal

Factors used in prediction

2. The Waterways Experiment Station soil moisture prediction method,

with modifications described herein, is used to predict moisture contents
on a daily basis. All measurements and predictions of soil moisture con-
tent in this paper are in terms of inches of water per 6-in. soil layer
above field minimum moisture content for that layer. Two layers, the 0- to
6-in. and the 6- to 12-in. soil layers, are considered. The predicted
moisture contents are used to prepare soil moisture maps. A discussion of
the factors used to predict moisture contents follows:

3. Initial moisture contents. If the rainfall during the month
preceding the prediction starting date was considerably higher than normal,
the initial moisture content was assumed to be the field maximum moisture
content. If the rainfall during the 30-day period was considerably below
normal, the initial value was taken to be the field minimum. A value of
moisture content halfway between field maximum and field minimum was as-
sumed following a 30-day period of normal rainfall. (The effect on predic-
tion accuracy caused by an erroneous assumption of initial moisture content
diminishes with time and ultimately disappears. See Appendix B, Effects
and Deficiencies of Factors Used in WES Soil Moisture Prediction System,
for details.)

4. Daily rainfall. Daily amounts of rainfall measured from Septem-
ber 1964 to October 1965 at 83 rain stations (fig. G1) fairly well distrib-
uted throughout Costa Rica were used. The minimum rainfall considered was
0.10 in.

5. Accretion relation. An accretion relation derived from data
collected at 170 sites in Costa Rica was used. The equation for this rela-
tion is:

$$M_2 = R - (R - M_1) \, e^{-0.80r}$$

where

    M_2 = final moisture content above field minimum

    R = moisture range of soil layer (field maximum minus field
        minimum)

    M_1 = initial moisture content above field minimum

e = 2.718

r = rainfall factor

where

$$r_{0 \text{ to } 6 \text{ in.}} = \frac{\text{rainfall}}{R_{0 \text{ to } 6 \text{ in.}}}$$

$$r_{6 \text{ to } 12 \text{ in.}} = \frac{\text{rainfall} - (M_2 - M_1)_{0 \text{ to } 6 \text{ in.}}}{R_{6 \text{ to } 12 \text{ in.}}}$$

6. <u>Depletion relation.</u> A depletion relation derived from data collected at the same sites as those used in the development of the accretion relation was used. The equation for this relation is:

$$M_2 = M_1 \, e^{-0.04t}$$

where M_2, M_1, and e are as defined above and t is time between rainstorms in days. For one day of depletion, this equation simplifies to:

$$M_1 - M_2 = 4\% \, M_1$$

7. <u>Soils.</u> Predictions were made for five soils with ranges of moisture content between field maximum and field minimum increasing in equal increments. All soils of Costa Rica fall within limits of the ranges. The ranges of moisture content for the five soils are as follows:

Soil	Relative Moisture Content Range	Range of Moisture Content Between Field Maximum and Field Minimum, in.	
		0- to 6-in. Soil Layer	6- to 12-in. Soil Layer
1	Very high	3.25	2.50
2	High	2.60	2.00
3	Medium	1.95	1.50
4	Low	1.30	1.00
5	Very low	0.65	0.50

8. <u>Field maximum moisture content.</u> Field maximum moisture contents of individual soils and soil layers were measured or estimated from soil, site, and climatic factors.

9. **Field minimum moisture content.** Field minimum moisture contents of individual soils and soil layers were also measured or estimated from soil, site, and climatic factors.

10. **Soil moisture range.** The soil moisture range was determined by measuring the difference between field maximum and minimum moisture content or was estimated from soil, site, and climatic factors.

Prediction data

11. To illustrate the system, daily predictions of moisture content were made for rainfall at one rain station, Turrialba. A computer print-out data sheet, shown as table G1, lists the predicted moisture contents for 24 days of record for the five soils mentioned. Predictions for an additional soil (x) are included in the table to show the application of the system to a soil with a frequently occurring moisture range not included as one of the other five soils. The same predictions as shown in the table may be obtained by interpolating the data between soils 3 and 4. Elements of the computer print-out include the number, depth, and moisture range of each soil, amount of daily rainfall in inches, and daily predicted moisture contents (above field minimum moisture content). The data for soils 1-5 are plotted in fig. G2. To show examples of variations in predicted moisture content with variations in rainfall, data from Liberia, Cartago, and Sarapiqui are plotted in figs. G3, G4, and G5, respectively.

Map preparation

12. A map of each 6-in. soil layer for each of the five soils was prepared for a specific day or season. The predicted moisture contents for the day or season (average of daily values) were shown on the map adjacent to the location of each rain station, and areas of equal range of moisture content were delineated. As an example, consider the map of Costa Rica in fig. G6. A prediction of moisture content is made for one soil type (soil 1), one soil layer (6 to 12 in.), and one day (31 January 1965). Each number on the map represents a value of predicted soil moisture content (above field minimum) at the weather station. This means that antecedent moisture conditions and rainfall amounts were considered at each station. Only three categories of moisture content are shown. Obviously, isopleths

of 0.1-in. increments and a larger number of categories could have been delineated, if desired.

13.   In fig. G7, the portrayal system for one soil and day illustrated in fig. G6, is expanded to three soils (soils 1, 3, and 5) and five days (31 Jan, 30 Apr, 20 May, 31 May, and 30 Sept 1965). The three-category moisture level (high, medium, and low) and legend are the same as those used in fig. G6. It should be recognized that the maps do not show the areal distribution of the soils. The maps, however, do show the moisture level of a soil with a given range only if that soil is present in the area of concern.

Determination of moisture content
for a given soil at a particular time

14.   The moisture content of a given soil and layer on a given day can be read from the map for the specific soil, layer, and day. The moisture contents of soils with ranges other than those mapped can be interpolated from the maps for the five basic soil ranges. If the absolute moisture content of the soil is desired, it can be obtained by adding the field minimum moisture content to the predicted moisture content.

Conclusions

15.   The system presented herein for predicting and portraying soil moisture contents in Costa Rica is relatively simple and straightforward. It appears to be applicable, with minor modifications, to other areas of the world. However, a considerable amount of basic data (i.e. soil type, accretion relations, depletion relation, etc.) would have to be acquired in a new area before the system could be applied to that area with maximum confidence. Nevertheless, it appears, from a cursory study of data collected in Thailand, Puerto Rico, Hawaii, and Panama, that soil type, accretion and depletion relations, etc., are interrelated in tropical regions. The extent of this interrelation has not yet been fully explored. It appears likely, however, that the system described herein can be applied, with some measure of success at least for strategic planning purposes, to other areas of the world for which only general soil and climatic data are available.
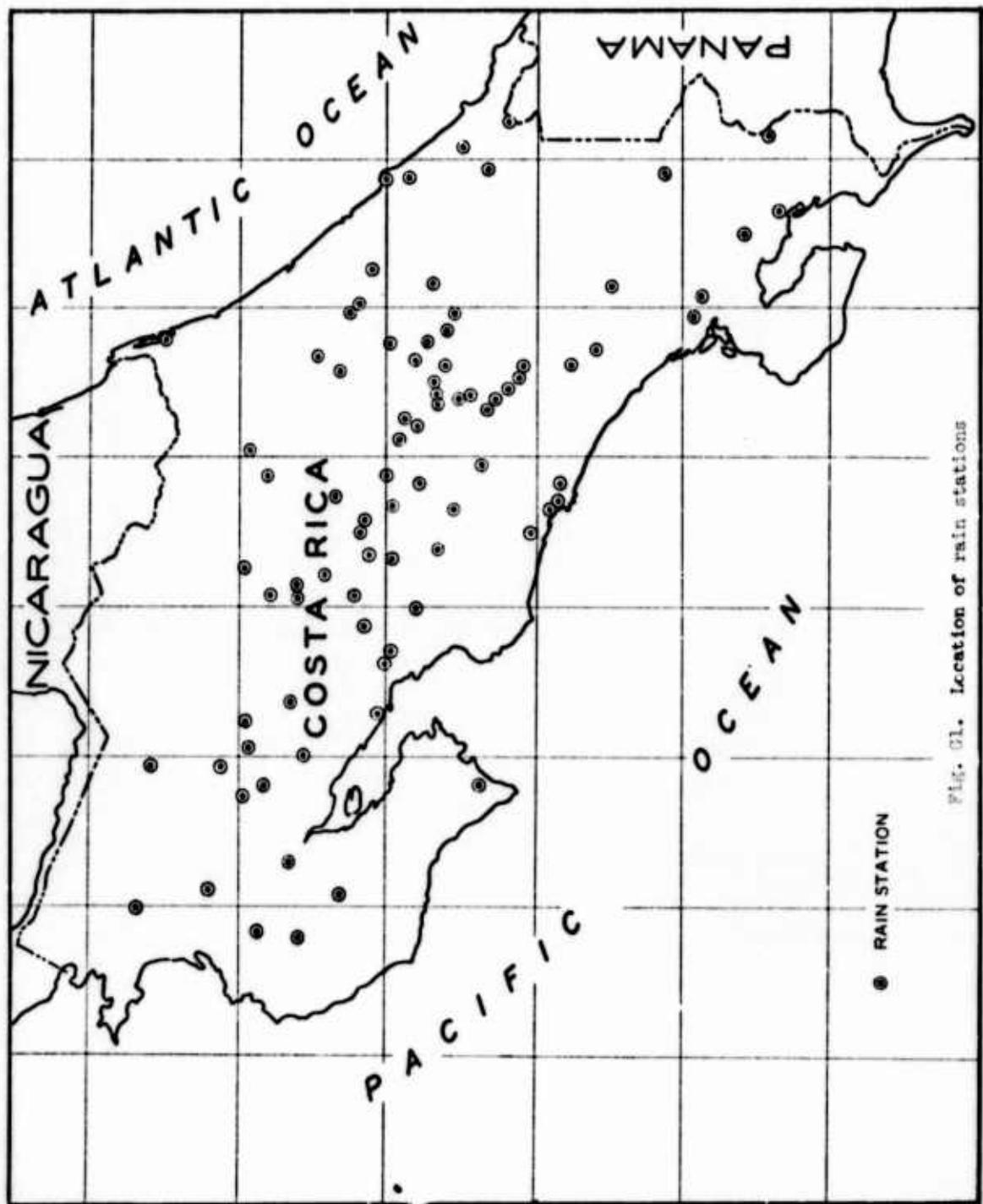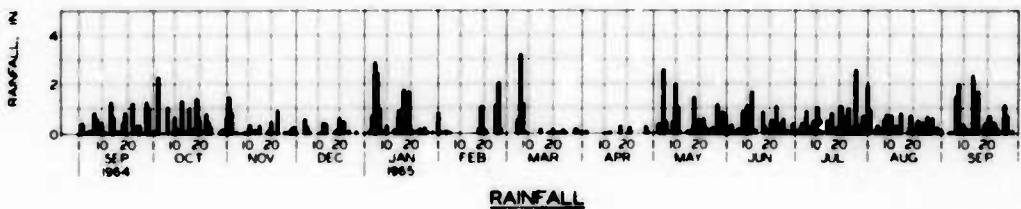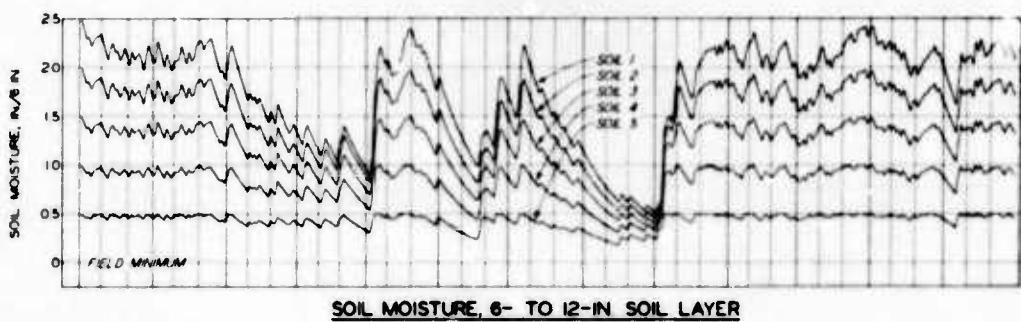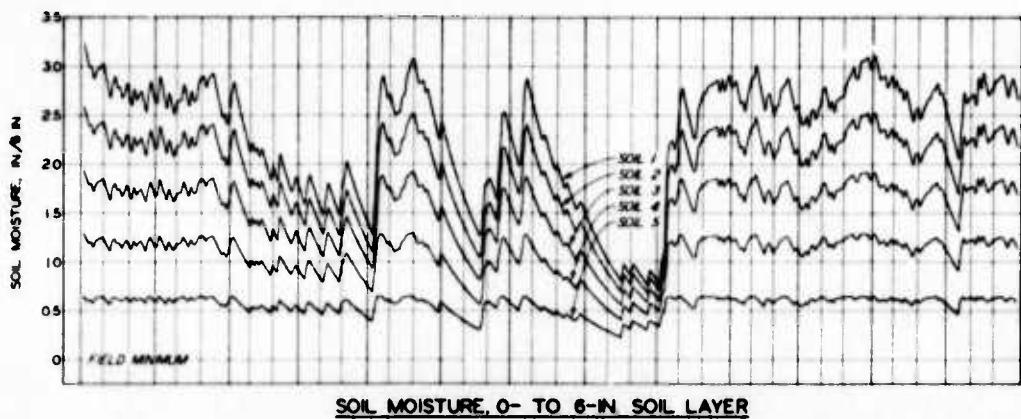
G5

Fig. G1. Location of rain stations

● RAIN STATION

SOIL MOISTURE, 0- TO 6-IN SOIL LAYER

SOIL MOISTURE, 6- TO 12-IN SOIL LAYER

RAINFALL

NOTE SOIL 1 – VERY HIGH MOISTURE RANGE
SOIL 2 – HIGH MOISTURE RANGE
SOIL 3 – MEDIUM MOISTURE RANGE
SOIL 4 – LOW MOISTURE RANGE
SOIL 5 – VERY LOW MOISTURE RANGE

RAINFALL AND PREDICTED
SOIL MOISTURE

TURRIALBA, COSTA RICA
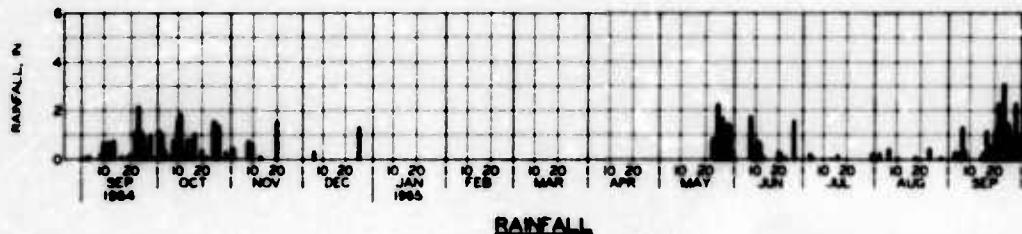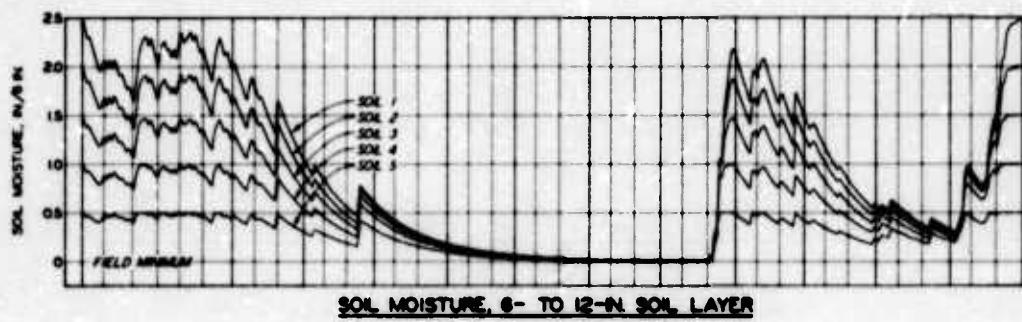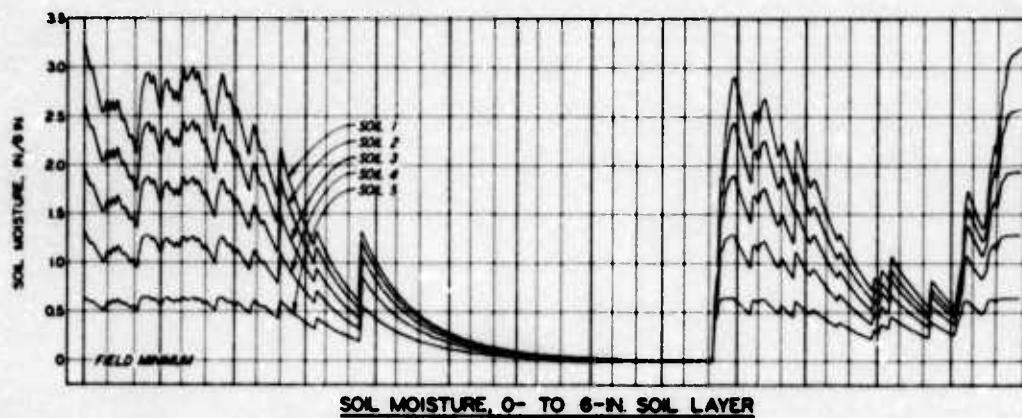
6-7

Fig. G2

SOIL MOISTURE, 0- TO 6-IN. SOIL LAYER

SOIL MOISTURE, 6- TO 12-IN. SOIL LAYER

RAINFALL

NOTE: SOIL 1 - VERY HIGH MOISTURE RANGE
SOIL 2 - HIGH MOISTURE RANGE
SOIL 3 - MEDIUM MOISTURE RANGE
SOIL 4 - LOW MOISTURE RANGE
SOIL 5 - VERY LOW MOISTURE RANGE

RAINFALL AND PREDICTED SOIL MOISTURE

LIBERIA, COSTA RICA
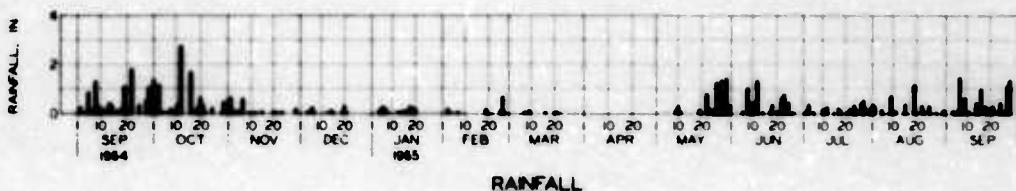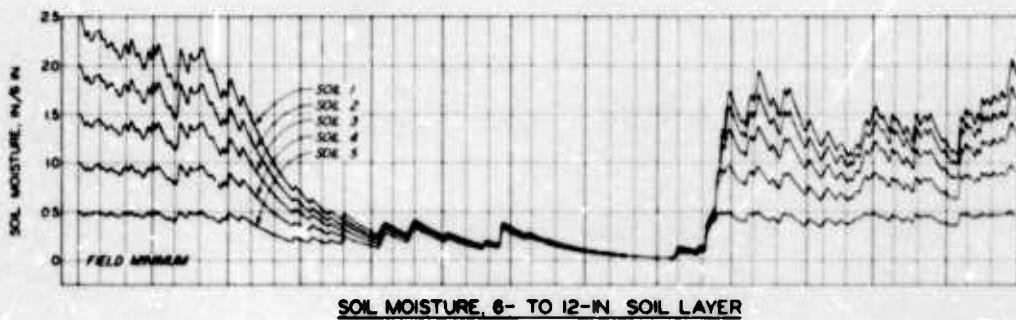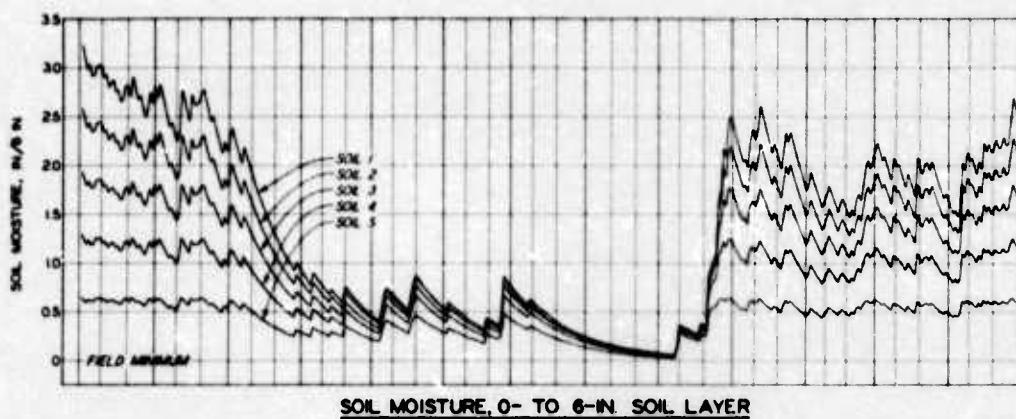
Fig. G3

G-8

SOIL MOISTURE, 0- TO 6-IN. SOIL LAYER

SOIL MOISTURE, 6- TO 12-IN. SOIL LAYER

RAINFALL

NOTE SOIL 1 - VERY HIGH MOISTURE RANGE
SOIL 2 - HIGH MOISTURE RANGE
SOIL 3 - MEDIUM MOISTURE RANGE
SOIL 4 - LOW MOISTURE RANGE
SOIL 5 - VERY LOW MOISTURE RANGE

RAINFALL AND PREDICTED
SOIL MOISTURE

CARTAGO, COSTA RICA
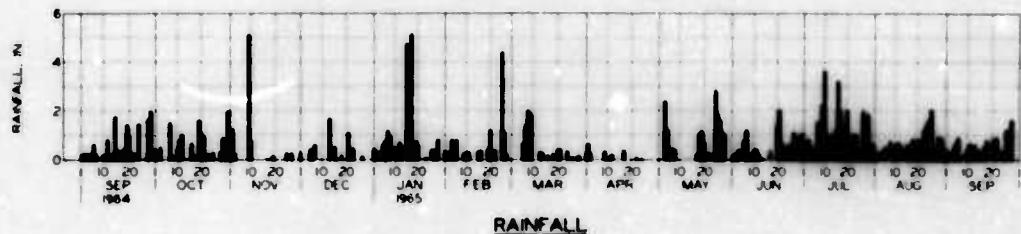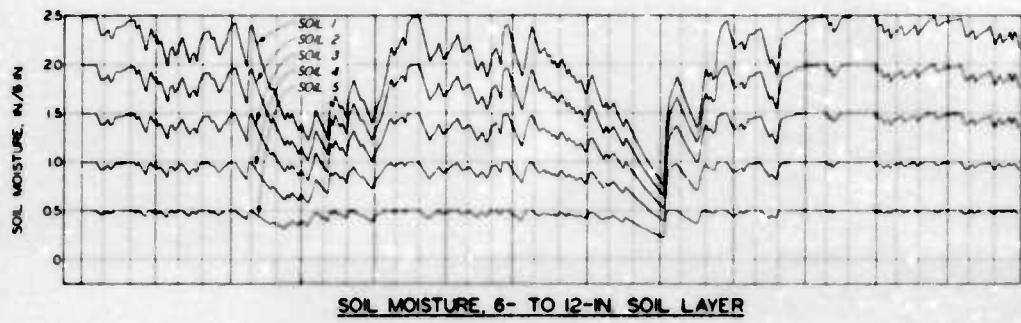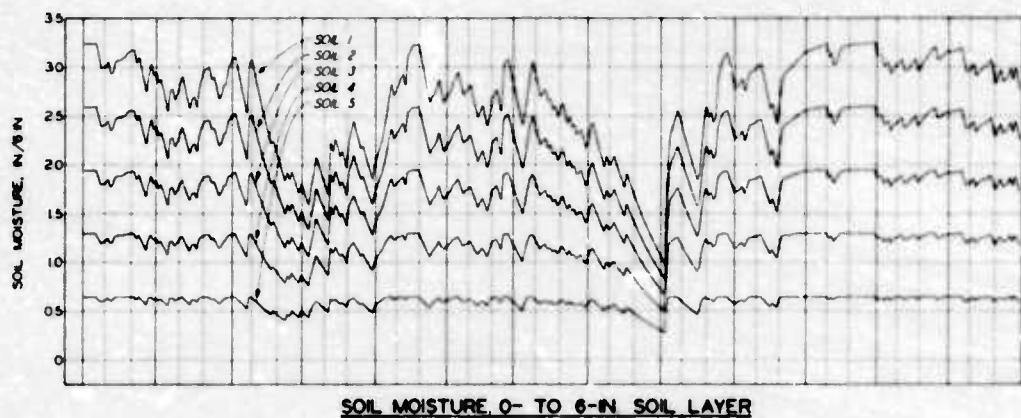
SOIL MOISTURE, 0- TO 6-IN SOIL LAYER

SOIL MOISTURE, 6- TO 12-IN SOIL LAYER

RAINFALL

NOTE SOIL 1-VERY HIGH MOISTURE RANGE
SOIL 2-HIGH MOISTURE RANGE
SOIL 3-MEDIUM MOISTURE RANGE
SOIL 4-LOW MOISTURE RANGE
SOIL 5-VERY LOW MOISTURE RANGE

RAINFALL AND PREDICTED
SOIL MOISTURE

SARAPIQUI, COSTA RICA

Fig. G5

G-10
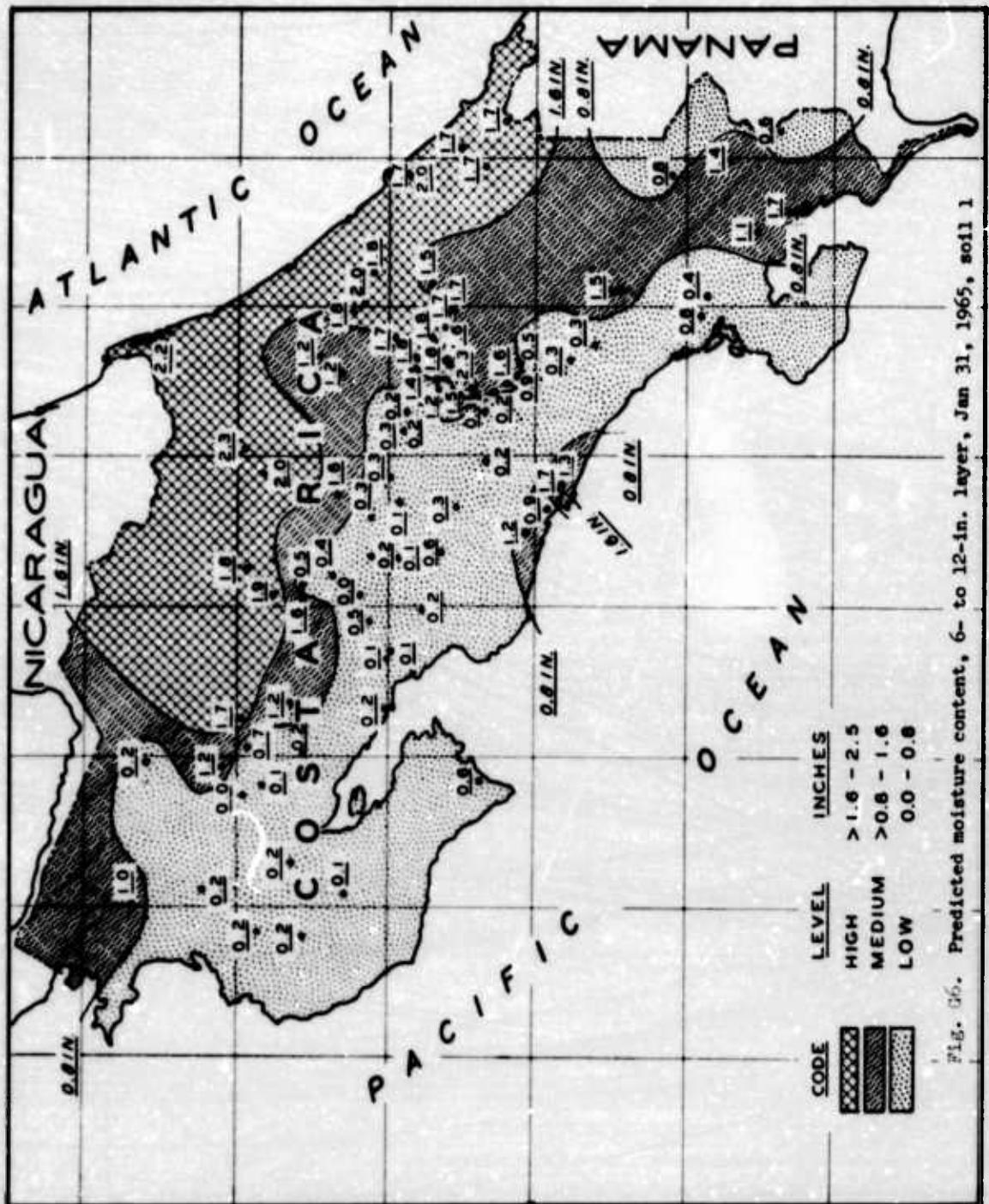
Fig. G6. Predicted moisture content, 6- to 12-in. layer, Jan 31, 1965, soil 1

PREDICTED MOISTURE CONTENT
6- TO 12-IN. SOIL LAYER
COSTA RICA
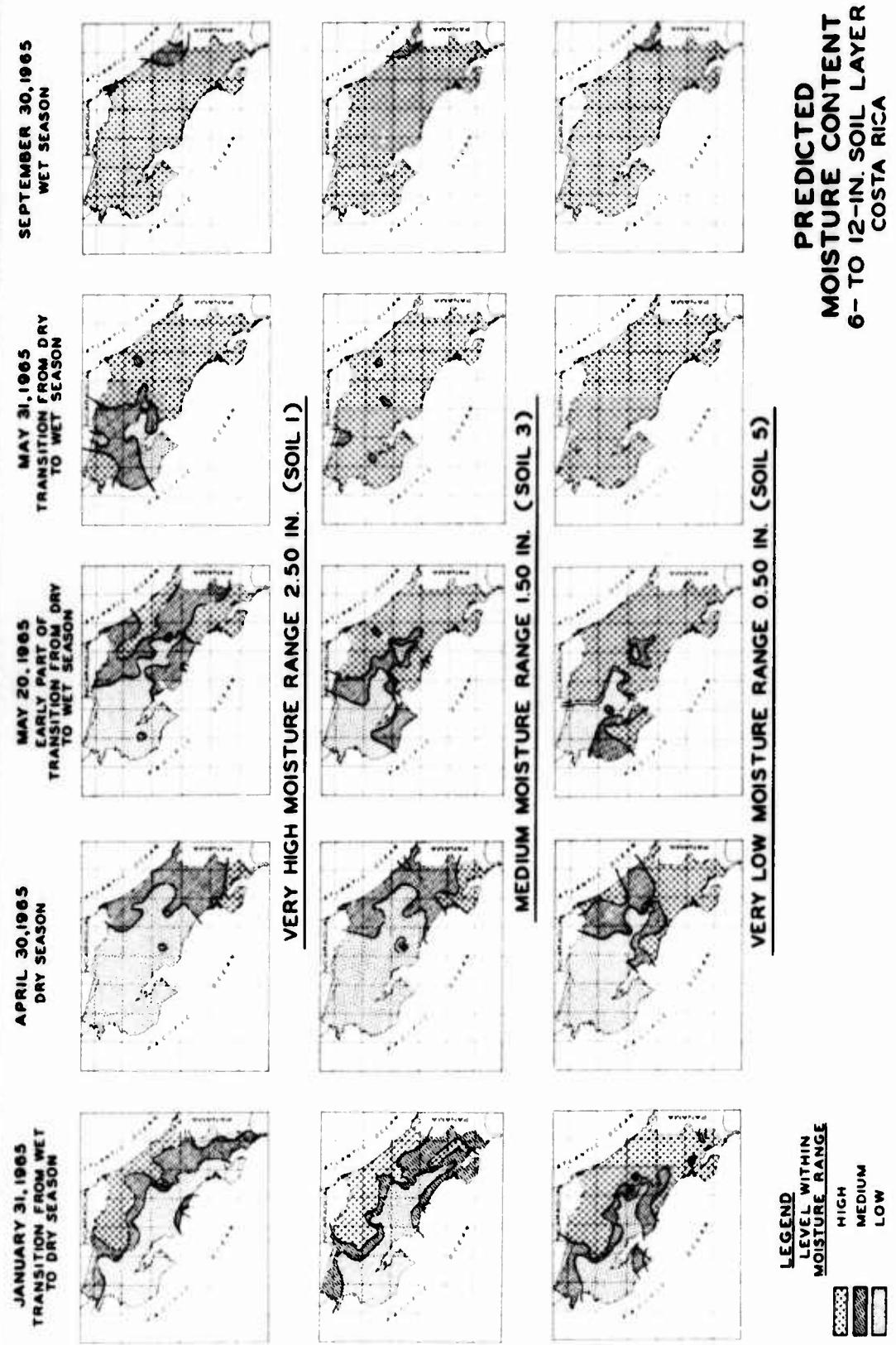
Fig. G7

Table Gl

Soil Moisture Prediction for Areal Mapping of Moisture for Well-Drained Soils

Location of Rain Gage: Turrialba, Costa Rica

Predicted Moisture Content, in.
Soil Moisture Range, in.

Day	Rain	Soil 5		Soil 4		Soil 3		Soil 2		Soil 1		Soil x	
		0.65 0- to 6-in. Layer	0.50 6- to 12-in. Layer	1.30 0- to 6-in. Layer	1.00 6- to 12-in. Layer	1.95 0- to 6-in. Layer	1.50 6- to 12-in. Layer	2.60 0- to 6-in. Layer	2.00 6- to 12-in. Layer	3.25 0- to 6-in. Layer	2.50 6- to 12-in. Layer	1.62 0- to 6-in. Layer	1.25 6- to 12-in. Layer
368	0.42	0.65	0.50	1.30	1.00	1.95	1.50	2.60	2.00	3.25	2.50	1.62	1.25
369	0.04	0.62	0.48	1.25	0.96	1.87	1.44	2.50	1.92	3.12	2.40	1.56	1.20
370	0.03	0.60	0.46	1.20	0.92	1.80	1.38	2.40	1.84	3.00	2.30	1.49	1.15
371	0.14	0.61	0.47	1.21	0.93	1.81	1.39	2.40	1.85	3.00	2.31	1.50	1.16
372	--	0.58	0.45	1.16	0.89	1.73	1.33	2.31	1.78	2.88	2.22	1.44	1.11
373	0.85	0.63	0.49	1.22	0.94	1.80	1.39	2.38	1.84	2.95	2.28	1.50	1.17
374	0.59	0.64	0.49	1.24	0.96	1.83	1.42	2.41	1.87	2.99	2.32	1.53	1.19
375	0.14	0.64	0.50	1.25	0.97	1.84	1.42	2.42	1.88	3.00	2.32	1.54	1.20
376	0.49	0.65	0.50	1.26	0.98	1.86	1.44	2.44	1.90	3.03	2.35	1.55	1.21
377	0.08	0.62	0.48	1.21	0.94	1.78	1.38	2.35	1.82	2.91	2.25	1.49	1.16
378	0.02	0.59	0.46	1.16	0.90	1.71	1.33	2.25	1.75	2.79	2.16	1.43	1.12
379	--	0.57	0.44	1.12	0.87	1.64	1.28	2.16	1.68	2.68	2.08	1.38	1.07
380	1.29	0.63	0.49	1.22	0.95	1.77	1.38	2.30	1.80	2.83	2.20	1.49	1.17
381	0.65	0.64	0.50	1.24	0.97	1.81	1.41	2.36	1.84	2.90	2.25	1.53	1.19
382	0.02	0.62	0.48	1.19	0.93	1.74	1.36	2.26	1.77	2.78	2.16	1.46	1.15
383	0.10	0.62	0.48	1.20	0.93	1.75	1.36	2.27	1.77	2.79	2.17	1.47	1.15
384	--	0.60	0.46	1.15	0.90	1.68	1.31	2.18	1.70	2.68	2.08	1.41	1.11
385	0.43	0.62	0.48	1.19	0.93	1.72	1.34	2.23	1.74	2.73	2.12	1.45	1.14
386	0.84	0.64	0.50	1.23	0.96	1.79	1.40	2.31	1.81	2.83	2.20	1.51	1.18
387	--	0.61	0.48	1.18	0.92	1.72	1.34	2.22	1.74	2.71	2.11	1.45	1.13
388	--	0.59	0.46	1.14	0.89	1.65	1.29	2.13	1.67	2.60	2.03	1.39	1.09
389	1.24	0.64	0.49	1.22	0.95	1.77	1.38	2.28	1.78	2.77	2.17	1.50	1.17
390	--	0.61	0.47	1.17	0.92	1.69	1.33	2.19	1.71	2.66	2.08	1.44	1.12
391	0.33	0.62	0.48	1.20	0.93	1.73	1.35	2.23	1.74	2.71	2.12	1.46	1.15

APPENDIX H: SOIL TRAFFICABILITY CLASSIFICATION SCHEME

by

M. P. Meyer

Contents

APPENDIX H: SOIL TRAFFICABILITY CLASSIFICATION SCHEME

Introduction

1. Trafficability, the ability of a soil to permit the passage of a military vehicle, varies principally with soil type and moisture content. Moisture content is influenced by numerous environmental factors, the principal factor being weather, the vagaries of which are well known. Depending on its moisture content, the trafficability of any one soil may range from absolutely impassible to easily trafficable. When one considers this and also envisages the large number of different soils to be found, the classification of soils according to their trafficability appears to be a very difficult task. However, the task is immediately halved if one recognizes that all soils are equally trafficable when they are dry, and under dry conditions there is no real need to differentiate them from each other. Considering wet conditions, the task of classification would still be difficult were it not for the fact that naturally occurring soils attain high moisture contents early in the wet season (defined later in this paper) and maintain them with little deviation for several months of the year. Since one soil type will have distinctly better or poorer trafficability than another soil type under wet-season conditions, classification of soils from a trafficability standpoint becomes feasible.

2. This paper summarizes a study of pertinent trafficability data collected from soil during the wet season over a period of several years by personnel of the U. S. Army Engineer Waterways Experiment Station (WES) and their collaborators. Summary data are presented as a scheme for the classification of soils from a trafficability standpoint. A detailed report of the data, including their analysis, the soil trafficability classification scheme derived therefrom, and related studies was published in 1961.*

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* U. S. Army Engineer Waterways Experiment Station, CE, Trafficability of Soils; Soil Classification, by M. P. Meyer and S. J. Knight, Technical Memorandum No. 3-240, 16th Supplement (Vicksburg, Miss., August 1961).

3. Data were collected from a wide range of soil types at more than 1300 sites located principally in a humid-temperate climate in the United States. At each site, moisture content and density were determined, samples were obtained for mechanical analysis and determination of Atterberg limits, soil strength was measured in suitable trafficability units, and depth to water table, topographic position, and other environmental features pertinent to soil trafficability were ascertained. Many of the sites were visited several times during the wet season.

4. A preliminary analysis of these data considered the effects on trafficability of soil type, parent material, topography, time since last rainfall, water-table level, grain-size distribution, plasticity, and vegetation. The present analysis is restricted to the most significant parameters, namely, soil types, topography considerations, and general wetness levels based on time since last rainfall and the water-table level.

5. Each of the sites examined was therefore identified according to its soil type, topography, and general wetness level. Since many of the sites were visited several times during the wet season, it was feasible to identify the same site at the two general wetness levels to be described. Pertinent trafficability data from all sites in the same soil type-topography-general wetness level category were then subjected to determination of statistical means and ranges. A comparison of the statistical means and ranges of these data serves as a technique for comparing and rating the trafficability of soils during the wet season, i.e., a scheme for classifying soils from a trafficability standpoint.

Soil Type

6. The soils were classified according to two well-known systems, the Unified Soil Classification System (USCS) and the U. S. Department of Agriculture (USDA) textural classification system. The scheme for classifying the trafficability of soil is therefore available in both USCS and USDA terms. In the interest of brevity, this paper is restricted to USCS terms of reference.

Topography

7. A study of the data revealed the feasibility of classifying the topography of a site into one of two classes, called simply "low topography" and "high topography." Low-topography sites were those at comparatively low elevation with respect to surrounding terrain, and high-topography sites were those at comparatively high elevation. Absolute elevations had no significance in identifying the topography class. The sites identified as low-topography sites were usually poorly drained. Sites known to have water tables occurring within 4 ft (1.2 m) of the surface at some time during the year were automatically classified as low-topography sites; sites known to be always free of water tables within 4 ft of the surface were automatically classified as high-topography sites. These sites were usually medium-well to well drained. Fig. 1 is a graphic representation of the two topography classes considered in this study.
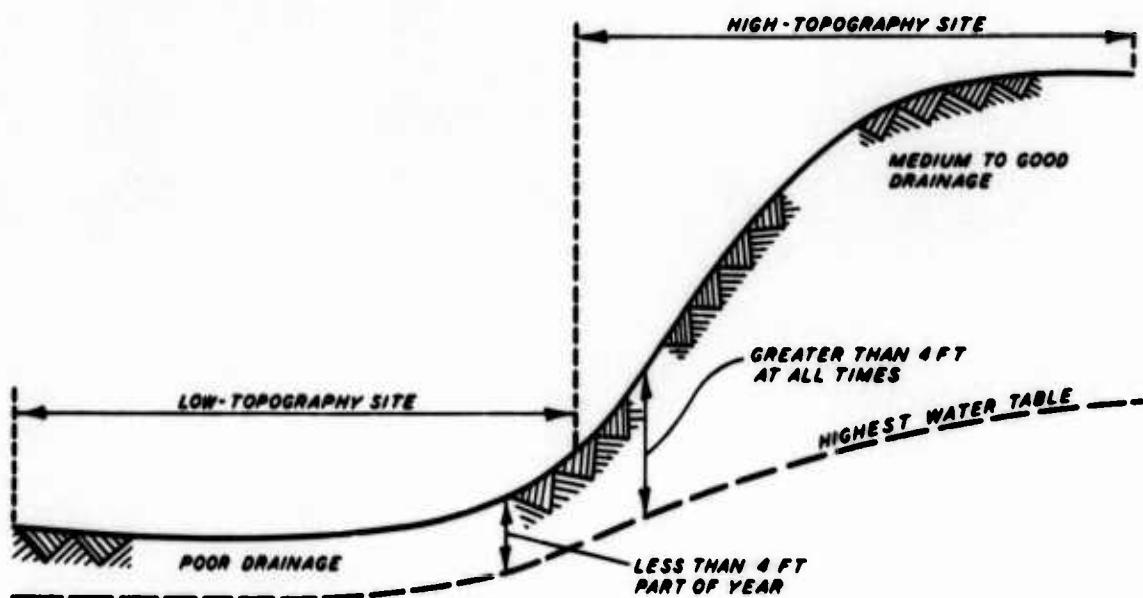

Fig. 1. Topography classes

General Wetness Levels

8. Two general levels of wetness, termed "wet-season condition" and "high-moisture condition," were employed in the analysis. Wet-season

H3

condition is the average of the varying moisture content of the soil in the
wet season. The wet season, defined as the period of the year of generally
high soil moisture, is one of generally high precipitation and low evapo-
transpiration, and it occurs in the winter and early spring months in
humid-temperate regions of the United States. The second moisture refer-
ence, high-moisture condition, refers to the highest moisture content that
may occur, i.e. during rains or immediately after rains. Fig. 2 graphi-
cally illustrates the variation in moisture content during the dry and wet
seasons for a low-topography site. The two general wetness levels employed
in this analysis are shown in the wet season. A high-moisture condition
also can occur during or following heavy rains in the dry season, but this
condition usually occurs infrequently and does not last long. High-
topography sites exposed to the same weather conditions would reveal a
more-or-less parallel moisture trace, but lower in values of moisture
content.
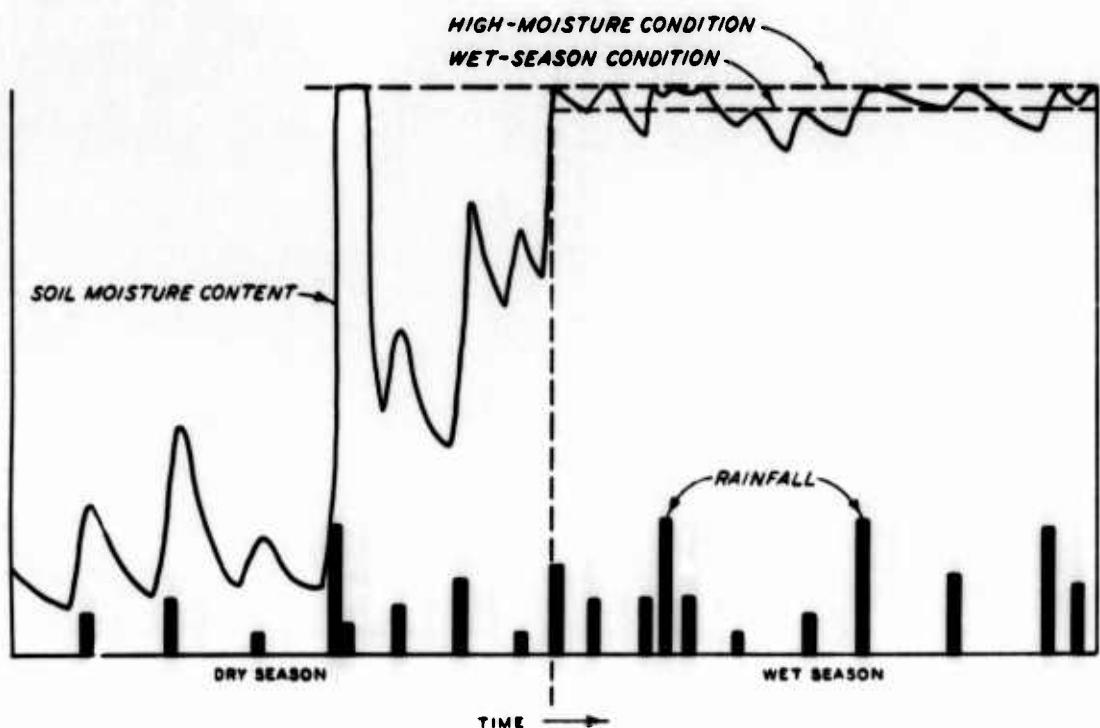
Fig. 2. General wetness levels for a low-topography site

H4

9. Absolute moisture content values under high-moisture condition for low-topography soils range up to 6% higher than values under wet-season condition, depending on soil type. The corresponding difference in terms of rating cone index, a measure of soil strength discussed later in this paper, is about 60 units.

Topography-General Wetness Level Categories

10. For purposes of the classification scheme, the topography and general wetness level references were combined into four categories as follows:

      a. Low-topography, high-moisture condition.

      b. Low-topography, wet-season condition.

      c. High-topography, high-moisture condition.

      d. High-topography, wet-season condition.

Because of the requirements for brevity, this paper discusses the classification scheme for only one category--low-topography, wet-season condition.

Soil Strength

11. The classification scheme is essentially a listing of soils in order of decreasing strength measured in terms of rating cone index. Data are from the 6- to 12-in. (15.2- to 30.5-cm) soil layer, which is the critical layer for most U. S. Army vehicles.

Cumulative Frequency of Rating Cone Index

12. If all the soils of a given soil type under a given topography-general wetness level condition always had the same strength, a simple classification scheme in which the rating cone index of that soil type is compared with the vehicle cone index could be developed to show whether a vehicle could or could not "go." However, the rating cone index of a given soil varies widely under a given set of general topography-moisture conditions. Therefore, the range of rating cone indexes that can occur must be

H5

considered. This was done by drawing a cumulative frequency graph and using it for estimating probabilities of occurrence of rating cone index values greater than a given value and, thus, probabilities of "go" for vehicles with a known vehicle cone index.

13. Fig. 3 shows the cumulative frequency (in percent) of decreasing rating cone index for a USCS ML (silt) soil type under low-topography, wet-season condition. ML soils for 104 sites were used in the analysis. Fifty percent of the sites had rating cone indexes greater than 77; this means that vehicles with a vehicle cone index of 77 would have a 50% probability of "go." Seventy-five percent of the soils had rating cone indexes greater than 47; thus vehicles with indexes of 47 would have a 75% probability of "go." Ninety percent of the soils had rating cone indexes greater than 32; thus vehicles with a vehicle cone index of 32 would have a 90% probability of "go." If probability of "go" is substituted for cumulative frequency in percent and vehicle cone index is substituted for rating cone index, a probability of "go" can be read from the graph for any vehicle cone index. This graph, as previously mentioned, is for ML soils under the low-topography, wet-season condition. Similar graphs have been developed from the data for other soil types and within each type for other topography-wetness level conditions. The graph for high-topography, wet-season condition shows a higher range of strength and thus would lie to the right of the graph in fig. 3. The graph for low-topography, high-moisture condition shows a lower range of strength and thus would be parallel and to the left of the graph for the low-topography, wet-season condition in fig. 3.

Soil Trafficability Classification Scheme

14. The product of the foregoing analysis, the soil classification scheme itself, is illustrated in fig. 4. The illustration includes only the more important USCS soil types and applies only to one of the four topography-wetness level categories, i.e. the low-topography, wet-season condition. (The complete scheme for USCS and USDA soil types has been included in the published report.) The predominant soil corresponding to the USCS soil type is shown in the second column of fig. 4, and the soils
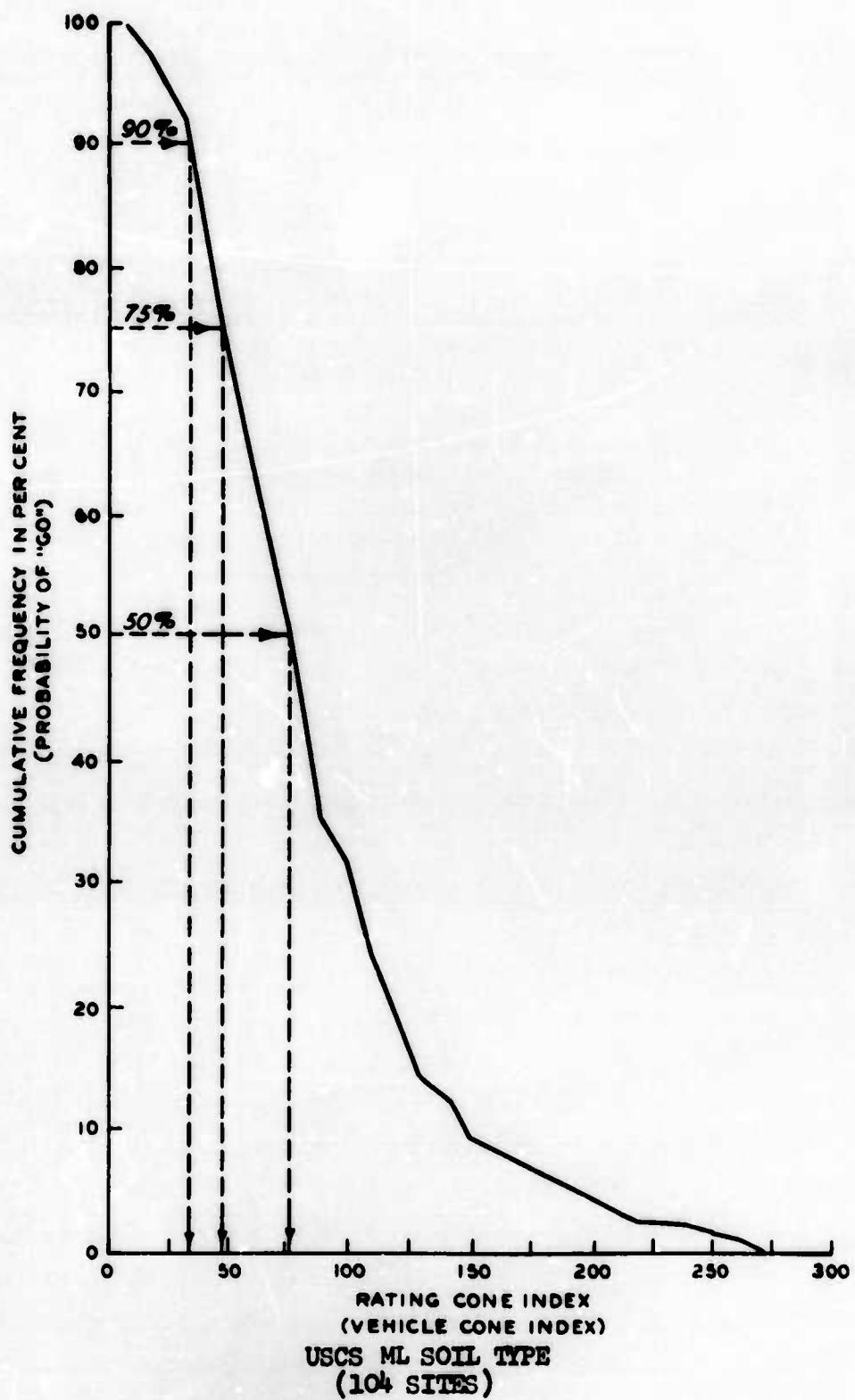
Fig. 3. Cumulative frequency of rating cone index for a USCS ML soil under low-topography, wet-season condition

H7

SOIL TYPE SYM	PREDOM. SOIL	MEDIAN RCI
SP	CLEAN SAND	-
CH	FAT CLAY	122
CL	LEAN CLAY	85
SM	SILTY SAND	85
ML	SILT	77
OL	ORG. SILT	54
PT	PEAT, MUCK	45

VEHICLE CONE INDEX

PROBABILITY OF VEHICLE "GO" ON LEVEL TERRAIN

☐ EXCELLENT - GREATER THAN 90%
▦ GOOD - 76 TO 90%
▨ FAIR - 50 TO 75%
■ POOR - LESS THAN 50%
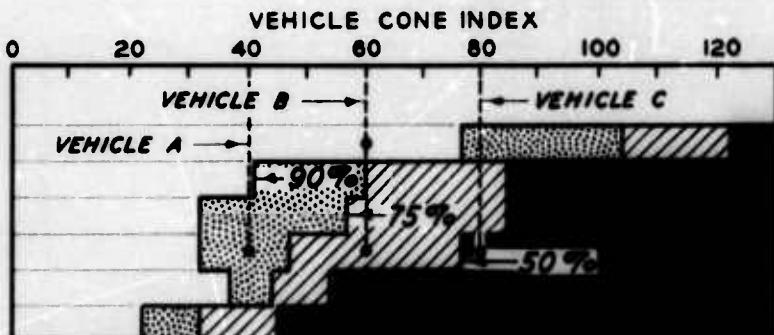
Fig. 4. Soil trafficability classification scheme in USCS terms for low-topography, wet-season condition

are listed in the order of their decreasing median rating cone indexes. The median cone index is the value of the rating cone index at 50% cumulative frequency and is represented in fig. 4 by the vehicle cone index value at 50% probability of "go." Studies have shown that the SP soils, the clean sands, are clearly the best soils from a trafficability standpoint. Unless complicated by slope or unusual conditions of high moisture, clean sands are trafficable to all tracked vehicles and wheeled vehicles with the proper tires and inflation pressures, regardless of the cone index of the sand. They therefore have been given a distinct place at the top of the list and have not been subjected to statistical analysis.

Probability of "go"

15. Probability of "go" was arbitrarily classified into four ranges, and each range was provided with a descriptive term. Greater than 90% probability of "go" was considered to be excellent; 76 to 90%, good; 50 to 75%, fair; and less than 50%, poor. The information is presented in the scheme (fig. 4) by a series of bar graphs, one graph for each soil type. Data used in determining the divisions for each graph, i.e., the vehicle cone index corresponding to 50, 75, and 90% probability of "go," were read from the cumulative frequency graph for the soil type. The vehicle cone indexes for the ML soil at 50, 75, and 90% probability of "go," as

H8

previously mentioned, were 77, 47, and 32, respectively.

Application

16. The classification scheme may be used in several different ways. As an example, assume that three different vehicles--A, B, and C--are being considered for possible travel over a low-lying ML soil area during a period several days after a rain in the wet season, i.e. under low-topography, wet-season condition. Referring to fig. 4, vehicle A with a vehicle cone index of 40 would have a good chance of success; vehicle B with an index of 60 would have a fair chance of success; and vehicle C with an index of 80 would have a poor chance of success. As another example, assume two different routes are being considered, one where the soil is ML and the other where the soil is CH. Vehicle B with an index of 60 would have an excellent chance of success on the CH soil and only a fair chance of success on the ML soil.

Limitations

17. The soil classification scheme has certain limitations. It was based on information for soils in a temperate climate and therefore may not necessarily apply to soils in other climates. A trafficability classification scheme has recently been developed for soils in Thailand; the USCS and USDA soil types exhibit strength ranges similar to those for the same types in temperate climates, suggesting that the classification scheme for temperate soils may be utilized in tropical areas. Limited information indicates that the scheme will probably be adequate for subarctic and arctic soils, but this remains to be verified. The scheme appears limited in that it applies to level terrain, but this limitation can be resolved easily by incorporating a slope index which considers the detrimental effects of a specific slope on the vehicle probability of "go." The scheme obviously does not cover the deterring effect of obstacles.

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